DECLASSIFIED PATENTS OF THE COLD WAR AND SDI

COMPANION STUDY GUIDE FOR "SECRETS OF COLD WAR TECHNOLOGY"

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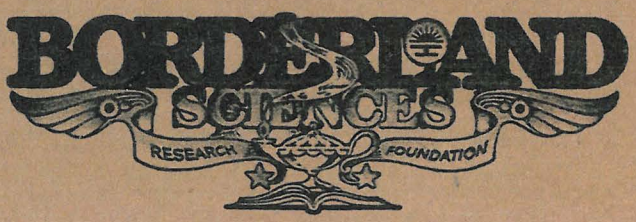

PO Box 220, Bayside, California 95524

DEDICATED TO WILLIAM LEHR

Devoted Scholar and Researcher,

Undaunted Experimenter,

Mentor, and Dear Friend

Who Passed From This World on Christmas Eve 1996

"For now we see in a glass, darkly..."

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Each of these patent texts elucidate several declassified technologies, priceless contents which reveal the true height and breadth of an alarming technology. Let it not be imagined, however, that this technology has remained as portrayed. What your eyes will presently feast upon represents technology which, though new to secular scholars, has already been superseded in countless new forms and parameters by its military developers. The importance of the technologies presented here does not lie in the specific devices which have been compiled. We are not impressed with the performance of devices designed to kill. We have no desire to counterfeit or improve the military designs, infernal machines. We are not enamored of technologies which permit dubious bureaucratic factions to engage in unsuspected and unbreakable security communications. Our true purpose is comprised of the thematic investigation of unknown natural phenomena, and if military patents reveal some new such mystery, we are intuitively compelled to search it out.

Understand then, that the bibliographic source of revelations concerning natural mystery is far less important than the revelations themselves. If we seem to be adventurers amid the bibliographic records, it is to uncover and unleash the conscious streamings of deep world mysteries. If thieves, then we are dispersing knowledge which has been too long imprisoned among those who serve their shadow masters. Such are the coveted gems of our scholarly devotions. The technological embodiments of anomalous and unknown natural phenomena are broadcast stations, noumenous radiators from which necessary epiphanies emerge. Technological embodiments are special sculptures, artwork whose unspoken messages deeply permeate into those who surround. Inventions emanate conscious radiances which stimulate new and unstoppable awareness, the catalyst which disturbs geopolitical control. All potential sources of this experience, scholarly documents and treatises, permit the development of a deeper and more archane worldview, one whose very frame reinvigorates the greatly advanced and highly desirable biodynamic technologies of our central thesis. Patent Texts such as these should therefore be closely examined. Assimilated and pondered from a distance, they are sure to produce serial and graphic mind elevations in their devotee.

This Patent Collection is divided into two basic categories: weapons and communications systems. The first group shows the progressive developmental trends in Coherent Beamray Weaponry. The latter group is devoted to Communications Systems, subdivided into three subgroups: modulators, detectors, and systems. The deeper details of each technology apprises the avid student of facts formerly withheld from university lecture halls and scholarly texts. For those whose passion it is to learn more of the mysterious phenomena which flood our world, such a study cannot be underestimated. While bureaucrats fear the loss of geopolitical control through the absolute ownership of such knowledge, access to the detailed information will stimulate a cataclysmic avalanche of new developments. One does not quench the flow of knowledge, while giving lipservice and vainglory to a now vague and ambiguous "liberty" in the selfsame breath.

It must be made clear that these patents by no means represent the whole fund of relevant declassified resources. This collection is but a small representative of the vast reservoir which awaits the thorough researcher. This tome began as the result of an accidental find. It was not originally the result of methodic and rigorous patent searches. Indeed, one finds the greater amount of highly revelatory Patents when conducting "random" searches. Seeking the microfilm cassettes of a particular time period aids greatly in this aspect of the search process. In this method, one often finds very well hidden patents in which astounding technologies lay quietly forgotten. We may trust that a principle of incomplete "truth in disclosure" is in force throughout the Patent Archives. But this incomplete status is not bureaucratic in origin. The filing of patents by megalithic competitors is predicated on financial weight alone. Issues of national security and high classification status is secondary to legal priority. What items fall through this priority sieve become

free issues of the intellectual domain.

One reads through these patents not without some shock, the sheer arrogance of each applicant permeates the too banal and routine descriptions of the deadly designs. After reading several score such patents, one very naturally questions the motive, the urge which prompts these researchers to proclaim their involvement in death-aimed technology. What is the "modus operandi" which prompts these technologically adepts to so fearlessly reveal their secrets before a cloaked assembly of international espions? One would think that greater discretion would be the poise, greater patriotism, far more conservative dignity at the very least. Ah, but no. We find quite the contrary. The pride, the pomp, and insensitivity in devising weapons to destroy people does not prevent them from openly and unabashedly declaring the effectiveness of these infernal tools. It is just because of this garish and gauche display of human folly, that one is led to question both the motives and purposes of those who do so. It is important for us to analyze and discuss the drive which leads supposedly classified researchers to publicly register a patent for some secret technology. If a device or utility is so very classified, why would any corporate structure actually make such a full disclosure; and by that act, risk theft at the hands of one's enemies?

At one time in our national history, it may not have been absolutely necessary for the citizen to become aware of military weaponry. With the inception of radiation weaponry however, and its potential use in oligarchy-directed "foreign operations", one is pressed to discover as much as possible. In addition, those who speak out in these matters have been characterized as "national security threats" by those who claim to preserve and protect freedom of speech. Knowledge, information, and its free exchange is not the foundation on which democratic republics are defined. The pillar on which democratic republics are based is freedom of speech without fear of bureaucratic reprisals, a condition which has not yet found its fulfillment. The total suppression of select individuals by bureaucrats is an indication of the modern bureaucratic attitude, a redefinition of democratic free speech. Knowledge is now feared. The potency contained in such a thesaurus of knowledge is much feared as a social catalyst of revolutionary proportions.

This Study Companion is intended to serve as a skeletal structure within which equally motivated students may easily launch forth into new patent searches. Let this text then be a branch in the large forest which has been recently uncovered. It is important to comprehend the implications of a government-provided patent search, there being no way to ascertain the thoroughness of such "given" patent registrations. The recent openness in Patent Archival reference is indicative not of a new bureaucratic spirit, one designed to stimulate the citizen toward new patriotic ideals. It is indicative of a completed project wherein all of the high priority classifications have been securely bound, while the once of secret, now-obsolescent technology has been relinquished. The filing and subsequent disclosure of highly classified patents already predicates the obsolescence of that which is disclosed. The present volume is the representation of already surpassed technologies. A discussion of the deeper implications inherent in these systems will form a running thematic commentary.

COMMENTARY

COMMENTARY SECTION 1

A SHORT HISTORY OF PENETRATING RADIANT ENERGY

1.1 ANCIENT RAYS

The main theme of this declassified patents section deals with various applications of a superior Radiation Technology, one whose very existence has not been suspected by the greater portion of the science community. While the fundamental theory of these systems could have been anticipated long ago, the issue has never been addressed in public forum. Except for a sudden insight received, during the course of research on submarine communications systems, I myself would never have ventured the supposition. Searching through the records revealed a flood of Radiation Technology patents, most having only very recently been declassified. The declassified status is affirmed by noting the awkward addition of dates on the patent headings. In addition, one notices that the presentation format of numerous such patents have been considerably altered; evidence that the design in question has been in bureau-interior litigation.

There is much to mention in regards to the bureaucratic process, where classified technologies become declassified, but we must first consider the sundry aspects of the technology itself before reaching conclusions related to these more geopolitical protocols. Please know then, that these patents do not represent the entire available fund. The retrieval of those innumerable others will require the motivations of your quest toward deeper understanding. In this emphasis then, each one of these patents has carefully been selected. Each is a specific representative, a chapter heading of an otherwise progressively long list of thematically variant developments.

The mythology and true history of beamray technology properly begins with the Egyptians, whose awareness of vitalistic solar energies prompted a pagan devotion to "Ra" the sun-god. The Egyptian mastery of natural phenomena enabled their marvelous achievements in numerous disciplines, not the least of which had to do with communications technology. Historians have great difficulty otherwise understanding how such large ancient empires were able to so long survive as singular organisms. Mounted on natural plateaus and mountainous peaks, large diameter and highly maneuverable silver discs effected the exchange of meaningful messages, and helps modern minds to rationalize and comprehend the large joined kingdoms. Available solar light supplied the necessary illumination by day, while sulphurated oil jets provided the brilliant light required to achieve and maintain nocturnal signalling. Egyptian mirror signalling techniques gave the ability to routinely transmit flashing light code across thousands of empire miles. This technology was deployed to produce other ancient world wonders. The lighthouse at Pharos (built 300 BC) provided its powerful beacons of light until an earthquake destroyed it in the 13th Century. Other, much smaller ancient lighthouses employed the same light concentrating power of the large polished silver discs, projecting powerful beams to twenty or more sea miles.

On behalf of the Athenian city state, Archimedes of Syracusa (247 BC) applied the Egyptian mirror technology to warfare. It was Archimedes, archetypal inventor, in whose control the living solar energies were wrangled into death-rays. His discovery of the parabola led to the development of superior concave mirrors, a means for the powerful concentration of solar energy. Archimedes represents the consciousness which demystifies Nature for the express purpose of effecting and extending human will. According to the legends, Archimedes enabled Athenian soldiers to concentrate enormous quantities of sunlight upon any prospective threat to the welfare and peace of the City. The simultaneous focussing of his multiple large diameter mirrors caused the instantaneous combustion of both enemy sailing ships and encroaching armies alike. Roman forces conquered the Athenian city state by planning their assault along directions which

frustrated the weaponry of Archimedes. Roman armies later appropriated this means to maintain battlefield communications, small tripod-mounted mirrors affording a compact and portable communications system. The use of mirrors in both communications and surveying applications followed western society through the time when the Templars ruled Europe. The Templars used mirrors for purposes of geomantic surveying and secret signalling operations between castles and cathedrals.

The Age of Discovery found mirrored communications systems absolutely vital for exchanging messages between and among distant ships and ports. This art remained essentially unchanged for centuries. The Eighteenth Century reemergence of portable Roman heliographs gives testimony to the fact that lost ideas remain. Until the Nineteenth Century advent of electrical science, beamray communications techniques largely relied on natural sources of light and flammable media. Lighthouses were vastly improved with the discovery of various illuminating gases, such as acetylene. The rapid development of inventions designed to best utilize these chemical illuminants gained popularity in the international maritime enterprises. Lighthouses and shipboard signalling systems employing acetylene and coal gas became part of the routine oceangoing repertoire.

The revolutionary developments in electrical science provoked an enormous technological flood, whose effects are yet resounding throughout the industrial world. The discovery of electroincandescent and phosphorescent phenomena became a primary focus for the invention of both illuminating and signalling systems. Systems for the powerful production of light and lightbeams fill the Patent Archive. The discovery of various electroradiant phenomena engaged the development of radio-ray and radio-wave technologies, developments which brought forth an awareness of invisible and insensate energies. It was within this awareness that new laboratory apparatus began releasing, modulating, and transforming energies of incredible potential.

1.2 RADIANT MATTER

Electrostatically induced luminescence was observed when a mercury-filled Torricelli Barometer was accidentally shaken, the vacuum space giving an eerie blue-green light (1630). Otto Guericke observed luminosity in low pressure "glass eggs" when electrostatic charge was applied to them (1633). Edward Nairne, a foreign member of the American Philosophical Society, observed electroluminous stratifications in low pressure cylindrical vessels (1711). Abbe Nollet demonstrated the effect of human contact on electroluminescent glass eggs (1747). Heinrich Winkler developed luminous displays when electrostatic charge was applied to bent low pressure glass tubes (1744).

Michael Faraday observed that the high voltage brush discharge from an influence machine actually produced chemical changes at a great distance from his high voltage terminal (1837). He took this to represent the extensive "dark discharge" which was propelled to the far surrounding space: evidence of energetic broadcast effects. Heinrich Geissler had invented certain improved vacuum pumps to achieve better conditions of low pressure than those obtained by Faraday (1845). Dr. Julius Plucker engaged Geissler to seal platinum electrodes in glass globes for the expressed purpose of studying electrical discharges (1847). Geissler independently discovered that low pressure gas tubes could be raised to phosphorescence by frictive rubbing, the addition of mercury greatly intensifying the effect.

Baron von Reichenbach asserted that highly stressed materials (magnets, mineral crystals, chemicals, metals, and plants) were focal points of a universal energy which he termed "Od light". Baron Karl von Reichenbach and his neurosensitives (1850) observed the strange and similar multispectral phosphorescence of magnets, crystals, chemicals, and pure elements in special darkrooms. He observed the large-volume rainbow displays of light which surrounded electrostatic charges; displays which greatly exceeded those lights normally associated with electrical action. In addition, Baron von Reichenbach found that

magnets extended a strong rainbow phosphorescence when poised in evacuated containers. He observed that the luminous colors actually grew in strength and volume with increasing vacuum. This he took as proof that the wavering rainbow colorations of auroral phenomena were produced by high aerial magnetic discharges of Od Light. Od Light was also present in solar, lunar, planetary, and stellar light; a component not recognized without certain filtrations and separations. Baron von Reichenbach was aware that these Od Light energies most strongly affected the viscera and emotive portions of human experience, and routinely proved these effects in several thousand experiments.

Geissler (1858) later prepared a great variety of wonderful low pressure gaseous electrical discharge tubes, some containing varied gaseous mixtures as well as electroluminescent chemical coatings. The more elaborate Geissler Tubes approached greater vacuum states, exposing chemically saturated lace, flowers, and chemically coated metallic patterns to high voltage electrical discharge. Inexpensive enough to be purchased as amusements, these phosphorescent displays provided an accessible public source of wonder. This proliferation stimulated and deeply impressed Victorian society with the sense that humanity had discovered some fundamental world mystery. Johann Hittorf (1868) produced more highly evacuated Geissler Tubes, observing that the stronger fluorescence of Geissler Tubes actually emanated from the cathode terminal. In this simple observation, Hittorf thus discovered the strange lightlike "cathodic rays".

Sir William Crookes (1875) undertook his detailed, methodic, and now classic investigation in order to test the Od-Light theory on electrostatic charge in high vacuum. According to theory, vacuum represented infinite resistance to the actual flow of charge. Sir William therefore expected that a rainbow display would flood the tube from end to end, just as Baron von Reichenbach described had been observed in open air. A series of marvelous electrical discharge globes were produced. Within these relatively high vacuum were seen smokey blue fluidic threads, which continuously wavered and intertwined. Sir William perceived how the behavior of these Od Light threads might have been influenced from an outside agency, movements highly suggestive of external control. Seeking access to the deepest vacuum states available, states which greatly exceeded the vacuum of all previous apparatus, Sir William began observing strange phenomena which had never before been viewed. The progressive extension of a strange black cathodic radiance was observed with increasing stages of evacuation, a presence which forced the luminous gas toward the anode. Crookes greatly wished to know the exact composition of this black radiance, and why it was able to drive off the luminosity in his tubes toward the anode.

At certain critical vacuum stages, Crookes could see wavering threads of black radiance merging with luminous threads of the anode; a very defined organic nature being revealed. He suggested that these fluttering, thready emanations were highly purified Od Light phenomena, made stronger than the ordinary electrical discharges by the evacuation process. This black radiant space seemed to drive the remaining luminescent gas out of the vessel with excessive evacuations, finally flooding the entire globe. At highest stages of evacuation, the entire glass globe fluoresced with an apple green color. The spreading black radiant glow was believed by Sir William to be a pure Od energy, one which actually preceded the appearance of Od Light phenomena. He strongly believed that this was strange evidence of space-distributed "ectoplasm", a space-filling living energy had been both purified and fractioned into clarified view. Within his high vacuum globes, Crookes believed that he had effectively contacted the world of spirit: a portal of access into the aetherial, unearthly world.

His views concerning the metaphysical currents flowing through his globes were never accepted by the Royal Society. To appease their inert view of the world, Crookes introduced dialogue on the material nature of cathodic rays. These, he stated, were streams of ultragaseous particles which moved through evacuated vessels at extreme velocities. Crookes designed several tubes by which the internal flow of black cathodic energy could be bent, and made to impact the walls. This quantitative analysis attracted the attentions of his Society fellows, a study which later produced a regime of beamray apparatus and particle accelerators. He reported the observation of a mysterious and penetrating heat, which flowed from the

black radiant space beyond the blunted walls of his modified study tubes. These were effects which could be felt at quite a distance. Indeed, glass at these blunted ends seemed to pressured, even to the melting point.

Crookes also observed strange phenomena which actually revealed the unity between phenomena taking place within his globes and those anomalies which now took place throughout his laboratory. Sir William observed electro-phosphorescent action both inside and outside his globes. The black radiant stream made chemicals and minerals glow. Many cited the possibility that the tubes were projecting a chemically active radiance in the deep ultraviolet spectrum. Nevertheless, Sir William could not account for the continual fogging of photographic plates which he had stored in special dark cabinets. Each experiment with the discharge tubes ruined his sensitive plates. Crookes delivered a discourse before the Royal Society on these phenomena, his famed "Matter in The Fourth State" (1879). But in keeping with his qualitative foundations, Crookes later described a visionary system of communications by which such globes and their rays could be utilized to signal through great distances (1890). Here we find the first recorded instance in which such a system is both described and afforded the possibility of construction.

1.3 DARKRAYS

Discovered throughout the Nineteenth Century, several varieties of various "dark radiant energies" were continually chronicled. These made their appearance in several distinctly different circumstances. Certain remarkable spectroscopic anomalies were discovered by Fox Talbot (1840). Talbot discovered light spectra, in which the usual low refraction of red and high refraction of violet colors, were actually reversed. Le Roux (1860) corroborated this discovery, finding the light-absorbing character of iodine vapor capable of effecting the same strange refractive reversal. De Klerker (1879) found that certain rays were not refracted at all in passage through similarly absorptive vapors. Such anomalously dispersed light rays were also found possessed of a material-penetrating ability not previously recognized. A hollow quartz prism was filled with fuchsine solution, and exposed to brilliant sunlight. Photosensitive plates, though well covered by a pasteboard cover, were fogged after exposure to the peculiar radiance. Plates, in a light-tight box, were covered by thick white blotting paper and other substances. Exposed to the dispersed rays, the plates were repeatedly fogged (Hodges). This demonstrated that anomalous dispersed violet rays have power to penetrate paper, leather, wood, and thick black cloth: evidence of unrecognized solar radiance.

To his already monumental discoveries, Baron von Reichenbach added a final triumph of his Od Theory. By successfully producing a remarkable series of photographic exposures, he demonstrated hard evidence for the existence of Odyllic Energy. Such exposures poised magnets and large crystals several inches from photographic plates, a very large focussing lens or concave mirror often being used to intensify the strange eternal light. It was found that Od Light required no lenses, their smokey projections passing from source to plate through tiny pinholes. These photographic methods set the stage for all of the successive discoveries made in subsequent years of the Nineteenth Century. Reichenbach produced true aura photographs, images of plants and human hands made with no other than their natural Od Light. These photographic exposures were later reproduced by Dr. Albert Abrams. Following the work of Kilner, a certain Parisian, Dr. Luys, used photosensitizing baths of hydro-quinone in order to produce aura photographs from the bodies of his patients. His discovery revealed the absence of strong auric emanations from paralyzed portions of the body.

In testimony to the assertions of Reichenbach, some experimenters used ordinary permanent magnets and successfully reproduced the clear images of objects (MacKay). Varying the original experiments, photographic plates were wrapped with strips of different metals in thick masking papers. Placed with a necessary gap, a fine order adjustment of millimetres, very ordinary permanent magnets produced a

remarkable series of "magnetographs" (Mace). In vacuum, these effects were corroborated by several other investigators (Wartmann, Hunt, Remsen). These energetic displays were produced by no other energetic catalysts but the magnets themselves. The use of dynamic energy in producing photographic images produced a new series of phenomena.

Professor Anthony discovered the penetrating power of sparks, perforating glass plates with high voltage discharges (1872). Scientific investigators had successfully produced very mysterious photographs, "skiagraphs", or "shadowgraphs" as they were then called. Electroshock images were routinely developed by Riess, Lichtenberg, Lullin, Fage, Sanford, McClelland, Piltchikoff, Duncan, Karsten, Nipher, and MacKay. These electrophotographs, sometimes referred to as "inductoscripts", were made in various configurations by which static shocks were applied to fine lycopodium dust, sulfur, diatomaceous earth, chemical gels, and photographic emulsions. The shock emanations from these electrostatic discharges passed through fairly thick close-contact layers of different substances, evidencing that many of their formations were due to anomalous rayic emanations. De La Rue produced electrophotographs across a space, the sputtered images forming within a well sealed container. Other investigators began producing photographs of well shielded objects by exposing them to the action of well distanced electrostatic machines. These long distance electrostatic photographs were produced by Case, Duncan, Dolbear, and Morton. The exposure of photographic plates to arclight energies produced a rare series of researches by Rittenhouse, Hart, Dolbear, and Tesla.

Several later researchers proved that sunlight contains penetrating energies, components capable of passing directly through layers of metal and thick organic multilayers. Repeated tests proved that unknown solar emissions were capable of rendering clear images in photosensitive plates. Solarigraphs were taken by Hammer, Morton, Rittenhouse, Schmidt, Case, Robertson, Kerr, G. Thompson, and Tesla. Zeugen produced remarkable night photographs of Mt. Blanc, some having suggested these to have been illuminated by "natural deep ultraviolet light". Dr. Gustav Le Bon discovered that heavily shielded oil lamps could produce incredibly detailed in equally shielded photographic plates, an anomaly. Dr. Le Bon employed special chemical emulsions to produce equally strange images of outer gardens, taken right through thick laboratory walls by a mysterious space radiance. In reiterations of the Reichenbach Od Light thesis, Dr. Le Bon stated that a continual radiance from space illuminated all matter. These mysterious photographs, which yet defy our present understanding, revealed that a cosmic illuminant passed through matter as if it were transparent. Dr. Le Bon continued his researches in this realm, proving the existence of strange matter-dissolving agencies in strongly focussed sunlight.

Others discovered a world of radiant emanations in the world of biology, where plants were found completely radiant in certain unexpected spectra. Vegetative emanations were termed "Tithonic Rays" by Dr. J. Draper (1841), who found it possible to develop photographic prints by exposing shielded plates to evergreen branches. The later work of Gurwitsch successfully explored this regime of vegetative energies, this work corroborating that of Draper, who found that such energies best passed through quartz glass before penetrating the shielding of photoplates. A fascination with rays and their penetrating power soon gripped the scientific world. In proof of the objective existence of the "dark rays", researchers began exposing heavily shielded photographic emulsions to various agencies, each of whom discovered a new and unexpected species of anomalous light.

The careful examination of these historical transcripts offers the devoted student insight into the vast reservoir of yet misunderstood world energies. The manner in which the plates were shielded (whether in lead, tin, or thick organic layers) makes it quite clear that the greater portion of such "mystery light" emanations were neither infrared nor ultraviolet energies. They therefore remain worthy of modern reexamination. These accounts are important in our development on beamray technology because they chronicle the vast reservoir of natural energies which had been discovered and forgotten: energies which yet may offer humanity a wondrous new avenue into deeper mysteries of the biodynamic world.

1.4 NIKOLA TESLA

Any discussion of Radiant Energy Technology necessarily begins with Dr. Nikola Tesla, whose legendary work on rays and beamrays formed the early and most formative origins of all subsequent radiation devices. It is imperative that we review his discoveries, since the forgotten fund of Teslian Science offers humanity the most clarified corridor toward achieving most of the modern technological quests. Teslian technology actually secured a wide range of potentials now thought impossible with real technology. In fact, the Teslian methods could yet obtain the means by which most technologically produced environmental hazards may be entirely eliminated.

In a single accidental find, Tesla secured the means by which a completely distinct kind of energy could be channelled. The phenomena accompanying this distinct energy have yet to be reproduced in the main. Those methods by which Tesla achieved his famed phenomena, conventionally impossible effects which he consistently demonstrated for a great many qualified observers, have not been viewed as special and distinct by contemporary research groups. Those who believe themselves in possession of better technologies have not been successful in reproducing the distinctively penetrating Teslian effects, those which render no harm to society when released. The attainment of more potent radiant effects than those achieved through Teslian methods has apparently never been successful. Researchers who sought interpretation of his achievements through particle beam systems found themselves engaged with lethal forces requiring excessive radiation shields.

The discoveries of Tesla properly begin after his development of Polyphase Technology. Tesla discovered a radiant electroshock phenomenon, the study of which eventually compelled him to abandon alternating current technology altogether. Tesla discovered this effect while performing experiments on violently disruptive capacitor discharges. The radiant electroshock phenomenon demonstrated the instant development of sensible shock and pressure effects at great distances from the apparatus. Its effects could be sensed right through copper plates, an obvious violation of simple electrodynamic laws. When wires were connected to his discharge device and immersed in oil baths, Tesla found that the focussed pressure effect could produce strong gaseous fountains. Tesla concluded that the effect was a new electrostatic force, and immediately set about studying its aspects to the exclusion of all other research.

In its strongest manifestation, Tesla generated and used only explosive impulses. Explosive, unidirectional capacitor sparks held the secret. Tesla sought means for producing steady successions of these explosive spark discharges, a means by which a sustained radiant effect could be secured. The very fact that these "electrified soundwaves" could sting human beings at a distance indicated the powerful radiant emission of electrical power from his apparatus. Tesla conceived and demonstrated a small system for the radiant distribution of electrical power, one which would supplant his own wired Polyphase System.

1.5 PULSATIONS

His problems were manifold: how to reduce the potentially lethal stinging shocks, and how to raise the intensity of the radiant shock power. Critical to the manifestation of this effect was the unidirectional discharge, a condition requiring specific resistance-capacitance relationships. Only properly configured discharge systems would produce the electroradiant effect. Through a revealing series of experiments, Tesla found that the radiant shock effect contained lightlike rays which were projected from the spark core. While spark intensity was the critical factor in projecting sufficient power from his apparatus, Tesla discovered that the duration of each spark pulse produced different kinds of distant effects. His development of various mechanical switches gave him certain control over the pulsation brevity. When the spark pulsations were shorter than 50 microseconds, the stinging pain disappeared. Tesla then devised a magnetic arc

disrupter, one which used the thrusting force of a strong magnetic field to pulse an explosive DC arc discharge. By adjusting the magnetic intensity of the gap and the electrical capacity of the primary circuit, Tesla was able to selectively modify the duration of each discharge.

Tesla discovered that the lightlike rays projecting from his magnetic disrupter were capable of producing strange and distinct effects on human sensation and matter, a spectrum of rayic effects never before observed. Decreased impulse duration produced pressure effects, penetrating heat, room luminescence, and cool breezes. But another observation stimulated Tesla to greater realizations, those which lead to the center of our discussion. The powerful magnetic field of this disrupter visibly thrust the bright blue arc completely out of the spark channel...its intended function. But Tesla observed a brilliant white fluidic stream which continued flowing between the poles, completely uninfluenced by the magnetism. This white stream of light was not merely composed of high thermal electrons, otherwise it would have been more powerfully thrust out of the discharge. Throbbing and pulsating in rhythm with the disrupted arc, this luminous white stream was responsible for all of the strange effects which he had been observing. A new current species had been fractioned and isolated. Tesla had discovered an entirely different species of energetic current, one which required the explosively violent electrical discharge for its stimulation. Tesla devised several special fractioning apparatus in order to separate this white luminous current from the commonly known electrical current. Indeed this bright white fluidic energy is that upon which Tesla relied for the production of all his legendary effects, a fact which has eluded and baffled researchers since his first announcements.

Tesla demonstrated the two distinct currents present in explosive sparks through several demonstrations. These each cleverly showed the distinction between electron currents and white currents. In one experiment, Tesla used a heavy "U" shaped bar across which several carbon filament lamps were connected. Stimulated by the aetheric currents of his Transformers, the copper bar became hot with electron currents, while the lamps became brilliant with a cold whiteness. His development of special white current Transformers provoked the intensification of projected rays beyond all expectations. These Transformers raised electrostatic tensions beyond all commonly accepted values, manifesting a strange non-magnetic induction phenomenon which surprisingly few could accept. The radiant streams, over which Tesla held strict priority, were electrically neutral and did not respond to magnetic fields. Tesla found that white currents fluidically wriggled over the surface of smooth, single layer coils. He was unable to measure an amperage on the coil itself, while developing electrostatic tensions exceeding several million volts.

White currents were absolutely harmless in passage through the human body, while handheld metal bars simply vaporized. The passage of the white currents through metals obviously produced charges, while passage through carbonaceous matter apparently did not. The fact that white current passage through certain metals produced electrostatic charge was a phenomenon which formed the very basis of his Broadcast Power System. His numerous experimental evidences were seldom comprehended, the dual current species not having been adequately comprehended or appreciated by most of the academic community. All except Crookes and a few German researchers.

1.6 RADIANT ENERGY

Produced by purified streams of the mysterious white currents, Tesla transformers became true Transmitters of the radiant force. Giving homage to his mentor, Sir William Crookes, Tesla termed these transmissions "Radiant Energy" broadcasts. Most engineers imagine incorrectly that this "transmission mode" required the agency of a long antenna. In other words, they view the Tesla transformer as a generator of harmonically alternating high frequency current. They are wrong. True Tesla Transformers are pulse transformers. Furthermore, they do not pulsate with electrical energy, they pulsate with white currents. The

radiant shocks pulse outward into space like successive shells of light, penetrating rays which require a simple ball antenna for efficient transmission. The rays can project outward from the large spherical terminals and powerfully produced a flood of electrostatic charges on contact with metals, a phenomenon which had previously been observed and misunderstood by Elihu Thompson in 1872.

Surmounted with copper spheres of specific volume, the Transmitters produced white fluidic near-zone discharges, and far-zone electrostatic power effects. This discharge brilliance was a condition which Tesla greatly wished to suppress. Besides focussing the radiant energy from a truly spherical distribution throughout surrounding space, the discharge streamers actually dampened the effectively transmitted power. Discharge streamers were not desired by Tesla, representing power drainage at the source. Even at this early stage in development, and despite the dampening effect of random streamers, numerous anomalies began to be noticed. Using Geissler Tubes in place of incandescent lamps, Tesla calculated that far more power was appearing at a distance than was actually supplied to the Transmitter.

Yes, Tesla found that the flow of power to the distant appliances often exceeded that which he was supplying from his high pressure terminals, an impossible condition. He was able to provide more than enough energy at a distance to bring specially designed motors and lamps to full operational performance. This feat was especially easy to accomplish when the Transmitters were grounded. Indeed, Tesla found that the Radiant Energy Transmitters were not propelling charge through space at all. Tesla observed that the radiant energy was producing charges only when impacting metal objects. Whatever this mysterious force brought through space, its principle essence was not electrical. This strange and penetrating radiance produced charges only on contact. Tesla very gradually comprehended that the radiant energy was simply stimulating a much larger atmosphere of energy, one resident throughout space. The white currents which he had generated, separated, and intensified held the secret.

Tesla showed that white currents could pass through most matter unhindered. White currents were believed by Tesla to be currents of an ultragaseous species, an aetheric gas which was discussed by Crookes and predicted by Dmitri Mendeleev. Mendeleev described the aetheric atmosphere as consisting of several distinct elements, noble gases very much lighter than hydrogen which flooded all of space. Tesla considered that the fluidic stream, which had successfully been fractioned from the violent chaos of his magnetic disrupter, was a purified stream of Aether Gas. He had intimated this in his very first publication on the electroradiant phenomenon, referring to the effect as taking place "entirely in the ambient medium". Composed of particles very much smaller than electrons themselves, this white aetheric current produced characteristic phenomena completely unlike those familiar to electrical science. The Tesla Transformer was like no other apparatus, producing a stream of throbbing non-electric aether currents. Tesla could skew the polarities of his Transformers, causing the aether currents to move outward from the high tension terminal...or inward, from all directions in space. This latter feature greatly intrigued Tesla, who recognized the space-permeating nature of the aetheric atmosphere.

The aetheric atmosphere filled all space. Therefore energetic stimulations were sufficient to set this atmosphere in motion. Aether evidenced a momentum unlike that observed when matter was set in motion. Aether required only a window through which to move. Thereafter, its own pressure would sustain the stream momentum. Tesla realized that his Transmitters were stimulating the very aether, setting in motion enormous potentials at a great distance. Aether engines! He designed a special transmitter for the expressed purpose of setting aether from space into motion, the magnifying transmitter.

Depending on the impulse rate and the material composition of insulators, white currents were found able to pass through electrical insulators. Here was evidence of their fundamental superiority as energetic species. Aether currents never passed through metal conductors without producing significant electrostatic charges, these appearing most powerfully at his Transmitter terminals. The high tension was produced not by the aether currents, but by the rapid accumulation of electrostatic charge. The density of metal resistances always resulted in the dramatic and rapid concentration of electrostatic charge, a process which

choked aetheric currents. Tesla observed this reciprocation, realizing that this had cloaked the existence of aether currents since the very discovery of electrical charge. Aether currents never tunneled into and through metals. Aether currents fluidically flowed around metals. Here was a progressive lesson which led to the new technology which Tesla finally perfected. The mere passage of aetheric current necessarily inferred energetic mechanical bombardment of the conductive medium. Metals represented a special class of elements which offered more resistance to the passage of aetheric gas. Aetheric bombardment of metals resulted in charge formation. While metals were best able to conduct electrical charge, they would not conduct aether streams.

These dynamics were recognized in his Transmitters, the insidious source of certain efficiency losses in transformation. The very metal of his Transmitters provided an effectively dense target for an aetheric bombardment effect to take place. This bombardment converted back some of the aetheric radiance into charges in the very moment of transformation, a discharge of brilliant white streamers. These streamers contained deadly components, electrostatic charges of unexpected potential. Sometimes lethal sparks often were unexpectedly discharged into the surrounding space, and were responsible for the near-tragic accident which occurred early in this research. Tesla replaced the copper ball antennas with low pressure gas-filled bulbs, finding that these safely projected aetheric radiant energy with far greater purity and efficiency. In this method, the deadly spark hazard was largely eliminated. The use of these gas-filled globes promoted the development of a new regime of technology, that which leads directly into our central discussion topic.

1.7 VERY SPECIAL RADIATION

Most Tesla students find this period of his research to be somewhat separate and radically different from that which engaged the development of wireless power broadcast systems and of geophysically coupled broadcast stations. But this is a misconception, brought about by lack of information. Tesla accidentally discovered that vacuum tubes could actually extend the efficacy of his Wireless Power Broadcast System in a most remarkable and unexpected manner.

The accidental production of several bizarre shadowgraphs occurred in the Tesla Research Laboratory at 33-35 South Fifth Avenue. The year was 1894. While using his gas-filled globes as photographic illuminators, strange prints convinced the photographer (Edward R. Hewitt) that something was awry. The peculiar characteristic of these gaseous lamps produced portraits which included the internal mechanism of the camera in use. Tesla recognized that the aetheric currents had achieved a potent degree of penetration after passage through the gas filled globes. The strange transparency of ordinarily obstructive material captivated Tesla, the dim portrait of his friends appearing among clockwork gears and lens casings. Tesla had not seen this effect with copper ball antennas. Tesla eventually replaced the gaseous bulb terminals with high vacuum carbon button lamps, having found that these conveyed aetheric force effects with greater purity and far less hazard. It was in conjunction with the implementation of these vacuum tubes that Tesla made his second greatest discovery, that which we will now detail.

His experiments with carbon button vacuum lamps revealed that a remarkable increase in the intensity of broadcast power was being effected. The rapidly pulsating flashes of energy could pass through walls unhindered.

Tesla found it a simple matter to broadcast both coded and vocalized signals on this far-spreading radiant emission. He experimented with the transfer of images through the radiant streams, a strange "magick lantern" system capable of projecting whole images through walls. Phosphorescent screens retrieved the images however distant. The discovery of fundamental phenomena eradicating the excesses of technical manipulations, the Teslian form of television required no scanning systems whatsoever. This

scheme was later revealed as a means for illuminating deeply submerged vessels of war. The Teslian submarine detector has always been misinterpreted as a primitive radar system.

Tesla began a new study of the white currents and their ability to powerfully project from a single electrode immersed in hard vacuum. A new investigation now sought the exact nature of the aetheric current, its composition, particle size, and other rare characteristics now revealed. The use of the vacuum tube as a conduit for his pulsating aetheric currents truly revealed new and unexpected attributes. Recognizing the ultragaseous stream which now flowed in powerful beams from his vacuum tubes, Tesla began performing a great number of tests to find how to better purify the radiant streams. Tesla discovered that the aetheric currents lost their brilliant white colorations when applied to high vacuum discharge tubes. Instead, a powerful black radiance flooded both the vacuum globe and then the entire laboratory space. In this intensified condition, one which greatly resembled conditions in interstellar space, Tesla learned more concerning the power of these aetheric currents than in all of his previous years of research.

Along with this clarified visual effect came certain defined sensations. When properly activated, these vacuum tube antennas produced strong elevations of physiological, emotive, and mental vitality. Tesla became obsessed with the notion that consciousness could be raised by such means. It is strongly believed that Tesla primarily designed his Wardenclyffe System to achieve a world wide transformation of these human parameters. A World Broadcast of such energetic influence would dramatically increase "human energy" on a social scale ("human energy" is a phrase originally coined by Albert Abrams in 1902, and refers to the human aura). A new mode of conveying energetic conditions now promised magnificent benefits for humanity. "Very Special Radiation" was the collective term which he gave to this new class of phenomena.

1.8 DUALITY

Sir William Crookes first termed the cathode rays and their ancillary energies as "radiant matter". The title could not have been more succinct. Ejected into a hard vacuum, from the very metal of a negatively charged surface, particles of vanishingly small mass became radiant projectiles. Launched along straight ray lines, such radiant matter represented a defined approach to the very condition of space itself. Radiant matter was some final nearly massless step before the vacuum state was reached. It was here that Tesla focussed all of his attentions, for in the comprehension of these concepts, one could develop a superlative energy technology capable of utilizing and manipulating the ultimate constituents of space.

The work of Sir William Crookes brought forth much scientific fruit in the haunts of experimenters everywhere. Crookes remained the loyal and trusted mentor of Nikola Tesla until the passing away of the elder. Tesla forever regarded Crookes as the greatest living scientist, the very one whose work in "radiant matter" research led him to his own scientific devotions. Tesla continued publishing his findings throughout the years, his column in the Electrical Engineer and other scholarly periodicals giving strong testimony to his originality in all phases of experimental process. Tesla was remarkable in his ability of arranging experiments. Observing and interpreting puzzling phenomena were delicate crafts of which he was clearly a master. Because of Faraday, Hittorf, Crookes, and Tesla, a great many experimenters set to work on vacuum tube phenomena.

By 1894, the scientific world was flowing over with discoveries concerning strange particle streams and rays. Each newly discovered energetic stream demonstrated the remarkable ability to penetrate matter, some more powerfully than others. In addition, these rays performed remarkable energetic transformations in their passage through both space and matter, evidencing numerous usable interactions. The fund of Victorian knowledge overflowed with a succession of discoveries in these regards, each of which strongly suggested an entirely new technology: a radiant energy technology, which utilized the strong interactions

produced by beamrays in order to transmit power and signals. This prospect, for Tesla, was a welcomed advent. Tesla had been describing these phenomena for a decade of more. His impulse systems were generators of low impulse rays, not producers of radiowaves. Tesla believed that his Transmitters were producing a "slow" form of light.

The mounting confusion in the world of physics poised its study on the nature of light. Experimental evidence suggested that light could behave both as a particle and as a wavelet. Tesla did not accept that pure visible light was anything like convoluted electromagnetic wavelets. Tesla believed that "pure light" was more in the nature of a particle stream. Degenerated light was a wavelet. The confusion among physicists could have been simply resolved by assuming that visible light was a collection of different energetic species. Both were produced in the sun, a conjunct stream containing particulate light and light wavelets: two distinct energy species. Tesla considered only the particulate component of light to be "pure light", the vitalizing component of sunlight. Wavelets produced all the damaging physiological attributes commonly associated with sunlight.

For these reasons, Dr. Tesla did not accept the common misconception that a continuity between radiowaves and light existed. Since "pure particle light" differed from degenerate light wavelets, one could never find unity between the two differing species. Those who stated it possible to produce light from superhigh radiowave generators had been completely misled. The pulsing rays which Tesla Transmitters powerfully generated were indeed more nearly lightlike, composed of aether particles. He believed that the rays projected from his Transmitters were the true origins leading up the scale toward pure particle light. Recently these findings have been corroborated by engineer, Eric Dollard. In a brilliant series of experimental verifications, Mr. Dollard demonstrated the distinct quality and attributes of light produced through the application of Teslian pulsed aether currents. The light is brilliant, vitalizing, more in affinity with pure sunlight, and offers strange pressure effects in keeping with the statements made by Dr. Tesla. Indeed, the Tesla aether ray spectrum began with the relatively "slower" pulsations of his Transmitters, and led up through the particle light spectrum. Aether particles produced the ray spectrum. Tesla realized that the ability to produce a differentiated stream of aether particles would lead to revolutionary technologies, capable of achieving undreamed ideals.

1.9 LENARD RAYS

These conceptions of Tesla were misunderstood. Most continued believing that light had "two qualities". Misinterpreting the classical experimental demonstrations, they began concocting a model which simultaneously accepted both attributes of light. This and other theories of the time manifested an academic predilection with contradiction! Careful examination of the history will reveal this trend in theoretical physics, where grossly misinterpreted experiments very rapidly became hardened doctrine. Scientific discovery in the academies and private laboratories of the world followed equally convoluted avenues of pursuit. One group of investigators concentrated their efforts on discovering the nature of the inert matter propelled from high tension cathodes in vacuum. Another group focussed their intentions on discovering the exact nature of rays produced by high energy cathode ray impact in gases and against solid targets.

One of the principle experimenters in this regard was Philip Lenard, whose development of remarkable vacuum tubes earned for him the normally difficult to obtain respect of Dr. Tesla. Lenard placed a thin aluminum window at the opposite wall of a high vacuum discharge tube, the cathode projecting its powerfully propelled high voltage streams through the window. Lenard successfully caused cathode rays to escape the confines of his tube, the aluminum window becoming transparent to the flow. Serving as both anode and window for a remarkable energetic display, the Lenard tube projected a powerful radiant agent into the laboratory. With this arrangement, one which held most researchers in absolute awe, Lenard was

able to produce the brilliant dark violet fluorescence of the very air directly in front of the window.

The column of light was understood to be an externalized stream of cathode rays, thereafter termed "Lenard Rays". This beamray often extended for several feet from the anode window, a combination of particles and lightlike rays. Lenard Rays caused brilliant phosphorescence in a great variety of minerals, chemicals, and low pressure gas samples. Thin foils of various metal failed to block Lenard Rays, while thin quartz slices extinguished the fluorescing power of the rays completely. The rays acted as chemical catalysts, exposing photographic films. Lenard studied the manner in which these externalized cathodic rays produced shadows and interference effects when caused to pass through metal geometries. He showed that several ray species were simultaneously present in the beams, using magnets and electrostatic fields to separate each.

Lenard could not bend the cathode rays when once they had passed into air, an effect on which Tesla often commented. The Teslian model of radioactivity viewed all natural occurrences of radioactivity the result of external bombardment. Radioactive matter was matter of definite density, capable of intercepting and absorbing the high velocity impacts of infinitesimal particles. In the Tesla model, these particles came from space, the chemical "Zero Series" of aetheric gases which Mendeleev had so championed. Target anodes represented the natural condition in miniature, an artificial arrangement illustrating similar, but not exact phenomena. Tesla drew much of these particle-impact models from the classic written by his mentor, Sir William Crookes. In "Radiant Matter", Sir William speaks much of the nature of matter and the ability of specific particles to pass through relatively thick plates.

1.10 EXPOSURE

The exposure of each metal to Lenard rays provided many experimenters with an early examination of atomic lattices. We have viewed the impact process as an hysteresis phenomenon, where homogeneous matter constricts under impact, consequently cavitating and dissolving into surrounding space. Matter is a repository of enormous information potentials, often termed "metaphysical". In this view, matter was not originally endowed with the inertia which now forms and defines our experience. Qualitative human involvement with matter does not teach of atomic structure, it teaches of qualities which surpass the merely physical attributes. When handled, material samples give distinct impressions which extend our concepts of sensation and the world.

The several hundred researchers, whose endeavors in these studies were chronicled throughout the scholarly journals of Europe, had long observed a great variety of invisible energy forms which they collectively termed "darkrays". The numerous accounts cross and recross the variant experiments by which investigators compared and examined the several such species. It was indeed possible to generate new ray species by simply employing any combination of metal cathodes or anodic targets. Besides the great number of photorecords which preceded the announcement of Wilhelm Roentgen, there were those who continually observed and reported darkray effects while operating high voltage electrical discharge tubes. Sir William Crookes exposed photographic plates to the action of his mysterious dark rays at a distance from the bombardment anode, obtaining shadowgraphs of a remarkably sharp and clear kind. The radiant emissions passing through the glass tube walls of his high vacuum tubes produced a series of photographic impressions, the first such darkray photographs having been made by Sir William Crookes.

In 1895, the scientific and social world became stirred with the supposed first-time discovery of a new form of light. In perhaps the first modern instance of media-induced fame, Wilhelm Konrad Roentgen was propelled into history. His observation of chemical phosphorescence beyond a high vacuum discharge tube was not an original discovery at all. Sir William Crookes, Tesla, Lenard, and others, had previously reported the very same phenomena. While these first priority researchers obtained phosphorescent images

and photographic prints of objects or material patterns, Roentgen had secured an early phosphorescent view through a human hand. Largely ignorant of the previous scientific proceedings, the public was completely enthralled by his publication. Roentgen entered the public spotlight, completely ignoring the fact that he had not discovered anything new.

Decades before Roentgen rediscovered the penetrating effect of X-Rays on the human anatomy, European researchers had already surpassed their work on the study with newer findings. Others had both performed and learned more concerning the mysterious rays, and offered humanity far more than Roentgen's little experiment actually merited. The accidental feat which captured the public eye and gained for him his place in the spotlight, proved only the power of public idolatry in choosing those portions of history and science for worldly fame. But electrical discharge phenomena, involving both invisible rays and particle beams, was the fascinating realm to which hundreds of relatively unknown names gave their scientific allegiance.

Several years of such research produced an enormous volume of experimental comparisons and tests in the scientific record. Each investigation sought the exact nature of the enormous spectrum of darkray species which had been found. The next step would be to comprehend how each distinct ray was related to the others. Certain researchers expressed the view that all of these vacuum discharge phenomena were the result of highly mobile aether particles (Wiedemann, Hertz, Goldstein, Tesla, Lenard). This would have neatly settled the dilemma posed by the existence of so many ray types. Fundamental misunderstandings concerning rays, particles, and waves prevented acceptance of the aetheric theory. Tesla had no doubts when considering these issues. Cathode rays were large particles, compounds made through aetheric condensations in metal lattices. He often described the strange explosive nature of electrons in certain highly energetic environments. No doubt he referred to conditions produced in his special discharge tubes.

1.11 SPACE ULTRAGAS

Dr. Tesla was able to prove that his powerful beamray projectors produced a neutral particulate energy, one which was capable of stimulating a wide variety of effects at their target reception point. Studying these varieties of longrange effects, Tesla opened a now forgotten world of secrets. Tesla had already comprehended the sequential transformations of neutral aether particles into particles of charge and mass. He viewed the Lenard discharge tube as a perfect arrangement for this purpose, the bombardment of target windows providing an easy means for examining such transformations. Tesla used a great variety of different metal windows, observing the effects of such collisions on the otherwise pure aetheric streams. Forced passage through the internal crystalline structure of metal targets proved instructive, the production of succinct aetheric compounds being the result. In modern terms, Tesla was studying the production of mass particles from the bombardments of a massless stream. In a great variety of experiments, tests which produced hundreds of experimental tubes, Tesla studied the means in which aether bombardment produced non-fundamental or "compound" particles. These would be classed among the catalog of particles studied by physicists today, particles which are claimed to be the "fundamental building blocks" of matter. Dr. Tesla always disagreed when these statements were early made by the academes, citing instances where the bombardment of fundamental aether particles resulted in spallation (recoil ejection) and condensation (mass production).

The process by which matter had been disintegrated by aetheric impact was chronicled a series of wonderful articles by Tesla throughout the latter part of the Nineteenth Century. But this study had its goal. He believed that the aether streams which flowed through his projection tubes were very close to the fundamental particle from which all matter was composed. Tesla later became interested in the commer-

cial application of these aetheric beams. The "improvement" of materials by bombardment, and the "conversion" of material elements from one species to another became his special fascination for a time. Tesla was deeply impressed with what had been revealed to him, now recognizing that the "Very Special Radiation", was pure and distinct from all of the other rays which had been discovered. Very Special Radiation was the primary materium from which all the other rays had been composed, the aether spoken of by the ancients. Aether was not quite matter, not quite energy, not quite space. Aether streams were a cross-over state in space, where energy and matter were in continual exchange. The vanishingly small aether particles were the next step to space itself.

While the quantum theory of Dirac sought to affirm these principles, physicists today reject the notion that Tesla had reached this ultimate material particle with the equipment he had at his disposal. The modern achievement the ultimate material condition would require extreme measures. Before seeking the penetrating impact and consequent dissolution of matter to such highly refined states, physicists usually begin with very massive particles. Accelerated nearly to the speed of light, they relativistically gather mass. On collision, it is supposed that they are capable of dissolving atoms beyond the ability of close-range nuclear forces to maintain the integrity. Few ever question whether the appearance of close-range nuclear forces, or any other forces, are the mere response of matter to high energy impacts. Forces and atomic centers suddenly appear, the hysteresis of homogeneous matter under irritating external impact. The Teslian method differed in the nature of currents developed, a current species obtained through manipulation of accessible natural conduction bands. Tesla had empirically stumbled upon a means for securing a neutral particle stream which, apparently, has never been secured by the methods common to accelerator physics.

1.12 VACUUM STATES

Dr. Tesla quickly advanced a theory concerning radiant energy transmissions which was never completely appreciated by the academic world. Having familiarized himself with the more common ray species, Dr. Tesla began seeking a select species for the service of a new technology. Dr. Tesla discarded the designs which produced Roentgen (X-Rays) and Lenard Rays (accelerated electrons), having secured a neutral radiation upon which he focussed all of his personal concentrations. The problem which the other researchers had failed to recognize was the means by which each had generated their varieties. Dr. Tesla realized why both particulate and photonic species were forming in the discharge tubes of other investigators. Few of his colleagues, if any, were beginning with a purified stream of infinitesimal aether particles. This was evident in the reports of those who claimed the so-called impossibility of striking an electrical discharge in hard vacuum. It had been believed that purely electrical discharges could not pass through hard vacuum tubes (Morgan, 1875). Even Lenard stated that cathodic rays could not be generated in hard vacuum. What this really meant was that electron currents could not propel cathode electrons into the hard vacuum.

Previous researchers were unable to produce such emissions from high vacuum, a product of their reliance on high voltage induction coil currents. Dr. Tesla found himself able to break both the vacuum and massive particle barrier by utilizing the aetheric currents of his unique transformers. According to Dr. Tesla, electrons were already condensed aether conglomerates and were far too large in cross section to escape the confines of the cathode lattice. But Tesla did not utilize electron currents in his Transformers. He used streams of aether particles. He was therefore not bombarding his terminals with the relatively more massive electrons. Discharges in the hardest attainable vacuum was never a problem for Tesla, who used single terminal projectors. In fact, Tesla used his aether streams to reach vacuum states which are yet otherwise impossible to rationalize.

Dr. Tesla described a special means for evacuating his tubes beyond the means afforded to others of his time. He first brought his tubes to moderate vacuum mechanically, a process followed by mercury diffusion pumping. Normal "outgassing" procedures followed. His final stage employed the use of high tension pulsations to drive away all of the remaining gas atoms from the tube. It was during this phase of his evacuation process that Dr. Tesla observed the "milky white" discharge which covered the enclosed terminal: the sign that aetheric streams were being released. After this "projective evacuation" process had been completed, Tesla sealed the tubes. The obtainable vacuum was virtually complete. In a later article, Tesla describes a much refined pulse evacuation process which requires none of the mechanical or diffusive priming pumps, the absolute vacuum being completed by pulses of special duration and repetition. Tesla published all of his findings in these regards. Most failed to recognize that his tubes were not being stimulated by electrical currents. He therefore continued obtaining effects which few, if any, could ever reproduce.

Dr. Tesla reported his ability to produce hard X-Rays capable of passing through the human skeleton, at a distance of 40 feet. In some cases, his tubes were projecting rays of greater intensity beyond 200 feet. But this was neither his goal, nor the radiant energy on which his new technology was to rely. Almost immediately with use, Tesla recognized inherent problems in his super vacuum pulse tubes. The purity of the aetheric current was being contaminated by virtue of material collisions within the tube. Aether currents were flowing with such penetrating force that they were mechanically generating and releasing a group of new energetic contaminants, particle species which Tesla wished to eliminate. Here were random and spurious discharges which, like those early occurring with his transformer terminals, were taking power and purity away from the intended broadcast radiance. Tesla wished to produce a highly purified aether stream, a stream of ultragas without particulate contaminants. Dr. Tesla had to find various means for separating and eliminating the numerous conjugate energy species released by his new and powerful high vacuum tubes; to eliminate the various species of particulate and photonic species released through haphazard internal collisions. He wished a purified and "monochromatic" stream of aether where possible.

The academic professions were already formulating and establishing theoretical frameworks by which to rationalize the existence of these new particles. Fixating their ideas according to established physical mechanisms, they selectively chose those principles which supported every other classical doctrine. This rendered the existing theoretical framework more sturdy, while denying the obvious evidence that Nature was teaching a deeper and more fundamental reality. With the exclusion of Victorian documents, one would never suppose the existence of any other but academic viewpoints. Nevertheless, one finds all too many comments, observations, and anomalous footnotes by names of the highest reputation, who offered differing views on the radiant and radioactive phenomena.

1.13 RADIANT SPECIES

With regard to Light and its associated phenomena, the scientific nomenclature of the time offers us a small notion of the lost science. That Victorian science which was reduced into a morass of abstractions after 1910 lists a progression of spectral names, lines above Visible Light whose distinct activities are unfamiliar to most. Measured by the light wavelet populations, it becomes clear that experimenters had distinguished very peculiar activities above the Visible Light Spectrum. Indeed, very specific chemical and biological phenomena were associated with specific Ultraviolet and X-Ray wavelengths (measured in Angstroms):

Rungling Rays	3200 to 3000
Hess Vital Rays	3100 to 2900

Heilbron Rays	2900
Morton Rays	2800
Kamm Rays	2700
W Rays	2200 to 150
Schumann Rays	2200 to 1800
Lyman Rays	1200 to 130
Grenz Rays	14 to 2

The very distinct effects of each given energies suggest the divergence of particle and wavelet populations at specific natural wavelengths, the so-called "particle-wave duality" representing two distinct but conjoint streaming energy species. In this view, the concept of a "photon" must be reexamined. This term may surreptitiously cloak the existence of two distinct energetic species: particles and wavelets. Indeed, it was early noticed that sunlight contains far more particulate species than wavelet species. Those who managed the production of shadowgraphs through the use of sunlight alone believed this distinction true. It was also early recognized that the vitalizing qualities of sunlight exceeds all sources of artificial light, biological processes being responsive to specific light spectra more than others. Some researchers gave strong suggestion that biological communications occurred on specific darkray spectral lines (Gurwitsch, Wuest, Rahne).

The discovery of natural radioactivity in 1895 by Antoine Henri Becquerel followed the announcement of Roentgen. Uranium minerals were found to radiate streams of particles, a seemingly constant and "immutable" process. Through various methods of separation, magnets and electrostatic fields, Becquerel was able to show the existence of "corpuscular rays" (large particles) having positive (alpha) and negative (beta) charges. Villard (1900) discovered Gamma Ray emissions from uranium, neutral rays which could be bent neither by magnetic or electrostatic fields.

Indeed, the broad spectrum of X and Gamma Radiation from radioactive substances was the focus of tremendous scientific attention, many substances being known only in terms of their natural ability to provide a free and prolific source of such energies. Uranium was thus found capable of supplying energies which spanned the length between hard Ultraviolet, long X-Rays, and Gamma Rays. Soft X-Radiations were once known as "Grenz Rays". Ordinary broadband X-Rays, those produced by the first X-Ray tubes, were termed "white". Monochromatic X-Radiations were once referred to as "unifrequent" rays (Hackh). Radium was perhaps the element which captured the most imaginative scientific exercise, the intense emissions from the element suggesting a miraculous new energy technology. Indeed, as originally conceived and designed, the energy of mineral radiance greatly exceeds the wasteful and common use of purified uranium isotopes in fission reactors.

But few considered the great number of emissions from natural sources and artificial discharge sources as much as did Nikola Tesla. It was important to learn what Nature was teaching concerning these energetic emissions. Were each of the now many recognized particles, as academes were so bold to claim, evidence of "fixed stable states"? Were there only certain particles permitted by some unrecognized natural law? Tesla disagreed. He had observed particles which were very much smaller than electrons, his ultragas particles. What made his observation critical had more to do with the "charge" of his infinitesimal particles: they were electrically neutral. Tesla continually stated that he was able to "manufacture" electrons and every sort of particle by passing his particle streams through various target windows. Here, Tesla claimed that particles were both being ejected and formed in the impact process.

Tesla studied the mechanism by which aetheric particles were actively being ejected from his pulse-energized terminal. Dr. Tesla sought means for enhancing the efficiency of this ultragas conduction process. He devised a great number of tubes, and conducted an enormous number of experiments. Most believe that Tesla performed these tests for reasons of pure pleasure in research. It becomes obvious

however, that his experimental studies were conducted with a view toward developing a new Radiant Energy Technology...one whose properties would completely supplant his own early and elemental designs for an electrostatic power broadcast system. The Colorado Springs Experimental Station and Wardenclyffe Station were to use the very ground as conductive media for aetheric broadcasts. Both of his gigantic geophysically coupled stations had been destroyed by the edict of financial concern. Rather than engage a wide space aether broadcast in the formerly conceived manner, Dr. Tesla now reconfigured his Radiant Broadcast System to concentrate aether power along tight thready streams. Beam power tubes would send the energy along a virtual powerline, between specific towers. The new radiant beam system could better control the energy supply between distant districts and regions.

1.14 AETHER TECHNOLOGY

Toward this progressive end, Dr. Tesla developed a hundreds of vacuum tubes projectors, which have largely been ignored by students of his technology. These designs have recently been described in a new treatise by researcher Jorge Resines ("Tesla Power Tubes"), designs which represent a Teslian venture deeper into the world of Aether Technology. The individual aether projecting tubes of Dr. Tesla, a very great variety, have been clearly drafted by Mr. Resines. Coupled with articles written and published by Dr. Tesla, we discover certain previously unobtainable and revealing facts. Most of his contemporaries reduced his developments in these regards, supposing that Tesla was simply producing intense X-Rays. Tesla was testing a variety of configurations intending to find those which maximized their aetheric output, while minimizing and defocussing the other degenerated species.

Tesla knew that the degeneration of otherwise pure aetheric streams properly began with their very release from the single tube-sealed terminal. Light metals were found best suited for this purpose, aluminum being the preference. Tesla beam projection tubes did not utilize targets. Tesla found that the sealed glass wall unfortunately degenerated the emerging aether stream into X-Rays, the source of his early difficulties. Replacement of this blunt glass wall with very thin windows of quartz solved some of the inherent problems. The aetheric "ultragas" could pass easily through this window without degenerating into collections of slow particles and wavelets, and without becoming agglomerated by impact into large "condensed" particles.

Commonly produced X-Rays, streams produced through reflective impact, consist primarily of wavelets rather than pure particles. Consistent with his thesis on Pure Light and the Pure Light Spectrum, Tesla considered X-Rays and Gamma-Rays to be complex blends of aether particles and wavelets. In such a mixed form, the radiant products of most experimental discharge tubes would pose a hazard to their human operators. Tesla was one of the very first to publish these warnings, after personally experiencing a laboratory mishap having to do with Lenard Rays. Tesla knew that a stream filtration principle would need to be discovered of necessity. When highly filtered streams of pure particles could be secured through the proper apparatus, then resplendent results would be obtained. Tesla affirmed that his experimental findings were consistent with the statements. He later reported the achievement of several otherwise impossible phenomena, and experimentally verified equally anomalous effects after the perfection of his special raytubes.

Tesla reported that his Very Special Radiation lowered the temperature of his ultrahigh vacuum terminals to below the frost point. This observation of coldness was corroborated (Amerio). X-Rays were actually seen by some observers, a strange spark-like sensation deep in the eyes (Tesla, Edison, Lenard, Dorn). X-Rays caused anaesthetic sensations (Tesla). In the Teslian mode, conduction produces energy streams entirely composed of particles. The purified X and Gamma Ray particles thus produced may not be the hazardous ionizing variety. We must consequently conclude that the rays, projected by the ultrahigh vacuum tubes of Tesla, were indeed distinct from all others. Tesla stated that vitalizing benefits could be

had by these ray species, a comment which again brought much derision. Familiar only with X and Gamma wavelets, one would be forced to agree with his conventional antagonists. Indeed, the high energy wavelets produced by vacuum impact tubes are hazardous. This energy species is entirely responsible for the production of hazardous ionization trails in biological systems. But the Teslian production of particles is predicated on the fractional elimination of all such "photon wavelets".

Recall that Tesla would expose himself to the energetic streams of his hard vacuum tubes with great regularity...and lived into his eighties. These daily exposures were never accompanied by any of the symptoms commonly associated with "radiation sickness", certainly not the malaise, the loss of appetite and vitality, the nausea, the loss of hair, and other deleterious effects. The results reported by Tesla are definitely related to the Gamma Ray therapy tubes of Dr. T. H. Moray, whose anomalous "soft" energy streams cured and vitalized as they soothingly passed through the human body. These developments in Teslian tube technology represented a true catalog. Each power tube was designed for a specific application. Tesla implemented each of several distinct particle streams in order to produce a specific effect. Some tubes were designed to transmute elements, others to both modulate and receive the human voice. Some were made for the powerful projection of usable power, yet others to receive that power. There were a series of powertubes designed for therapeutic purposes, elevations of vitality being the result.

Misinterpreting every one of his breathtaking demonstrations as a peculiar manipulation of mere electrical action, the very best experimenters have remained frustrated with Tesla. Their own inability to reproduce his demonstrations has taken the form of a mere interpretation and minimalization of Teslian Science. In its strongest expression, one finds a strange derision especially prevalent among professional engineers in this regards. But the complete breakdown of dialogue between Teslian apparatus and electrical apparatus is the best evidence that Tesla had indeed discovered and used a completely different energetic species. Only a renewed study of Teslian Technology and a willing openness to accept the facts, can bring these issues to their anticipated conclusions. Tesla thus stands in stark contrast against the contemporary corps of well funded engineers, who are yet unable to perform his simplest of demonstrations.

Tesla used the explosive energy of very powerful and brief unidirectional electric discharges in order to stimulate the release of a strange silverwhite stream, a particulate emission of now-unidentified nature. This stream, fluidic and organic in character, was electrically neutral: a flow of particles having none of the characteristics listed in academic compilations. The phraseology of Sir William Crookes ("radiant matter") was modified by Tesla ("radiant energy") when referring to his special discharge streams. But these silverwhite streams had properties never observed before or since Dr. Tesla first brought them into human experience.

SECTION 2

BEAMRAY WEAPONS

2.1 EARLY BEAMRAY GENERATORS

Recall that the historical wonder of the "dark" radiant energies centered about their strange ability to pass through the most opaque objects. With the exception of but a few select substances, these energies were found capable of passing through most metals with relative ease. More powerful radiations were gradually discovered through empirical testing, radiant energies which actually exceeded the penetrating power of X-Rays themselves. Whether correctly or incorrectly, some researchers equated these penetrating neutral radiations with naturally occurring Gamma Rays. Gamma Rays of sufficient intensity were found capable of passing through steel plates and even thick lead plates.

Working with both energy species, researchers quickly discovered the ability of these rays species in heating matter to incandescence. Crookes early discovered the ability of cathodic rays to melt little holes in the blunt tube walls of his more developed discharge tubes. Tesla recounted the various phenomena by which his Very Special Radiation actually punctured discharge tubes. So very great were these extreme pressures, from within the tubes, that Tesla observed the continuance of the streams despite punctured walls. In this phenomenon, Tesla had discovered the secret of aetheric pressure; a means by which special engines could derive motive force. In addition, Tesla tested and demonstrated several devices capable of producing motive drive through beamrays alone, fabulous light sources having tractive forces. In addition, Tesla had early found ways for communicating to very great distances along the radiant beams of these Very Special Radiations. Teslian communications required only a small radiant emitter, a vacuum globe. The dark radiant output of these systems surpassed those weak wave systems of Marconi, permitting vocal transmissions and receptions through walls. These were the benign uses of wonderful phenomena, having equally benign utility in the service of humanity.

There are indeed several good uses for radiation energies, not the least of which is found in the communications arts. The others find their use in various critical therapies, most of which vitalizing varieties have been suppressed by federal agencies of dubious alignment. Yet another use of radiation energies has much to do with materials sciences, the improvement and generation of substances being a principle theme. Indeed, there are uses of radiation energies by which hazardous materials may actually be neutralized and rendered safe, but these are matters for another publication. All these utilities are more easily rationalized by scholars and experimenters than this first discussion which requires mention. But there were those whose military assessment of radiation apparatus considered their utility in more deadly alignments.

With the developments of Phillip Lenard, cathodic emanations were brought outside the discharge tube and into the laboratory space directly. These rays were a puzzling phenomenon which most eventually treated as a harmless effect in air. In this naivete, many risked their health, eventually discovering the inherent dangers of the Lenard Rays. Recall that Dr. Tesla employed special excitation means, by which also the emanations from his special tubes were entirely distinct from the normal species reported by others. Nevertheless, Dr. Tesla found that when his Very Special Radiations were made to pass through target windows, their resultant impact radiations were very dangerous at close range. He and others found that penetrating Lenard Rays passed through the hands, producing a glow in the space beyond. In addition, Lenard Rays produced a warming effect on the body. This was an effect which later became the cause of greatest alarm among these experimenters.

2.2 DANGEROUS EMANATIONS

Long term exposures to Lenard Rays produced severe external and internal "burns". Tesla was first to report their painful aftereffects, burns which permeated the hand. He later reported that he had chanced to "look into the target plate" from a somewhat close range. The resulting "internal cacophony", knocking sounds heard within the skull, give an hideous impression to those who read the account. After so direct and potent an exposure, one would imagine that the life of Tesla was greatly curtailed. Yet Tesla lived well into his eighties, apparently of quite sound health. We have discussed the plausible explanation for this increased vitality, the differences between Teslian ray emissions and Roentgen X-Ray emissions being total.

Tesla very clearly differentiated between those dangerous emissions, obtained at close distances from the Lenard Tube windows, and those which projected to further distances. An assistant chanced to stand too close to a special Lenard tube, while Tesla conducted a lengthy series of experiments. The resulting burns across the abdomen so greatly upset Tesla, that he was compelled to confess the nearly fatal error. This contradiction implied that the greater projecting rays, normally thought to be of far greater lethality, were actually less hazardous than those produced directly from the window target itself. But these observations would be completely in accord with those statements consistently made by Tesla when describing his particular species of Very Special Radiation.

This was not the account given by other researchers, whose systems very obviously produced far too much of the hazardous varieties. Tesla reported that his sensitivities to the more harmful X-Radiations became ever more clarified with continued experimentation. He described a defined whole-body "tension" which gripped ray-exposed researchers with the very first close of the power switch. In addition to this, there was an effect on the eyes not unlike that caused by exposure to a brilliant light. Some experimenters reported that this sense of "brilliance" caused them to squint (Lenard, Edison). These strong visceral effects, though caused by an invisible radiance, were not without their lethal effects.

After the Tesla report on X-Ray hazards, Edison quickly came forward with the sad confessions of his own experiences in this respect. An assistant of Edison (C. Darrow) worked long hours, while the latter was developing his X-Ray fluorescent lamp. The assistant received mysterious deep burns, an unexpected trauma. These burns permeated the body, gradually spreading across the affected area in malignant growths. Sadly, tragically, the assistant eventually died from the exposure. It was a shock which brought Edison to report the fact that X-Rays had done permanent damaged to his own eyes as well. Several investigators began assessing the lethal potential of certain X-Ray species, whose motives are now not entirely clear. The serial discoveries of new, and more deadly radiations, were always accompanied by reports of lethalities in various animals.

There is that use of radiation energies which has nothing at all to do with the intended blessings for which these energies have been revealed to us: for, as soon as the inherent danger of the darkrays was recognized, their weapons potential was sought out by more devious and self-aggrandizing inventors. It becomes clear that Lenard tubes were the starting point for experiments in particle-beam weapons, where highly accelerated cathodic rays are propelled in gigantic bursts through appropriate metal windows. A great number of patents describe the varieties of impact particle and wavelet release. The variant forms of this method use targets of different metals and shapes in order to effect a specifically blended lethal emanation. Certain therefore produce neutron beams, others relativistic electrons, yet others X-Rays and electron complexes. Indeed, frighteningly powerful variations of the Lenard system which saw their inception throughout the years between World Wars did not cease for several decades after World War II.

One of the earliest recorded attempts at implementing X-Rays for military application was performed by Borgmann and Gerchun, the results published as "La Distance Explosive" in Comptes Rendue (17 February 1896). These tests followed those, earlier chronicled in the works of Turpain, MacFarland-Moore, and

Ulivi (see parent text); devices capable of causing the directed wireless explosion of enemy munitions. A history of World War I Beamray devices is contained in Volume 10 of the Vril Compendium, numerous newspaper clippings detailing interviews with an aged Nikola Tesla. There are a number of articles which were taken from various popular sources of the time period between World Wars, articles which described and showed the operation of "death ray" devices. It as been surmised that the inventors of these systems rarely received patent license for their systems because of the classification status. Our more critical readership would interject the plausible "inutility" of these systems, while failing to recognize the fact that the popular journals reported the military investigation of the same. A few of these "lost" patents appear among these pages as early Cold War weapons designs. Such technology defines the state of warfare, invincible beamray weaponry for both defensive and offensive operations.

Cathodic rays caused phosphorescent green spots to appear on the walls of Crookes Tubes. X-Rays were found to most strongly emanate from these glowing spots, places where the cathode rays had found and maintained an exit site in the glass walls. Wherever cathode rays were blocked from their electrostatically acquired high velocity, the X-Rays appeared. It was thus early learned that the slightest deceleration of cathodic rays resulted in the release of X-Rays. This, the product of particle impacts in deeply seated target electrons, X-Rays were the "braking radiation"...or "bremsstrahlung", taken from the German. The greater the change in cathode ray velocity, the greater the resultant X-ray intensities. This principle was applied to comprehend the continuous release of X-Rays from certain radioactive materials. The explosive release of electrons from such materials necessarily required the continual internal collisions of these same electrons with the nuclei through which they moved. The continual braking decelerations imposed on these high velocity electrons were responsible for the production of a natural X-Ray flux from certain radionuclides.

2.3 RAY OPTICS

Sir William Crookes discovered the ability of shaped cathodes and anodes in modifying the central discharge column within his vacuum globes. By these means he was able to project mysterious beamrays outside the confines of his discharge tubes. Anodes poised at angles to the cathode diverted and reflected cathodic emissions through the tube walls. It was Crookes who also discovered the ability of concave cathodes to focus the cathodic rays. It was by this method that Sir William was able to cause diamonds and other gemstones to fluoresce, heat or vaporize metals, and compel vane rotors to spin within his globes. The optical characteristics of cathodic emissions was further exploited in the development of X-Ray tubes, where combinations of concave cathodes and angled anodes produced intense X-Ray emissions in a specified tube-external column. Cathode optics was the principle means by which Dr. Philo Farnsworth was ultimately able to successfully produce contained nuclear fusion reactions with control.

Based on these conceptions, very powerful X-Ray tubes had been developed before World War I. Double concave cathodes focussed high voltage cathodic emissions on conical targets to produce X-Ray intensities never before realized (Swinton, Rice, Stine). The development of thermionic anodes, heated to incandescence by thick filaments, produced high density X-Ray beams of measured consistency (Coolidge). The improvement of target materials, with the notable replacement of platinum by tungsten (Langmuir), helped companies such as General Electric to rise in prominence as the premier producers of X-Ray apparatus. The use of X-Ray apparatus in medical professions had already become a matter of routine practice. The development and deployment of military X-Ray weapons has thus been historically cloaked behind descriptions of "medical" applications.

Before and during World War I, the intriguing science of X-Ray optics began to attract a small number of investigators and inventors. More a theoretical quest than an expected field of discovery, several of these

individuals sought some means by which X-Rays might be refracted, focussed, collimated, and reflected. Tesla and others had already performed experiments which showed that X-Ray beams could produce secondary emanations from objects into which they were directed. The reflection of X-Rays was thus a process of absorption and reradiation. A very large collection of phenomena in these regards had been gathered. These empirical findings described a wide variety of elemental responses to X-irradiation, the different elements becoming either highly responsive or opaque to the same. X-Rays were studied with a rare curiosity, the radiance itself representing the very essence of the unknown to researchers. X-Rays seemed to be messengers from the depth of space, beckoning attention and consciousness.

X-Rays were found to diffuse around sharp edges (Edison), and continue through a series of successive reflections (Lafay, Thomson). Tests had been performed to determine whether the rays could be polarized (Mayer, Quincke, Elster, Geitel, MacIntyre, von Laue) or made to mutually interfere (Roentgen, Perrin). In order to extend the knowledge of X-Ray optics, experimenters employed special pinhole shields in order to collimate the rays (Leeds, McBerty, Scribner, Stokes). Others developed special metal lenses, showing a very real and surprising refractive effect (Stine). Until Max von Laue proved the refraction of X-Rays in crystals (1912), each early such test produced questionable results. Using crystals of zinc sulfide or rock salt as effective diffraction gratings, von Laue actually measured the wavelength of X-Rays. Moseley later discovered a means for identifying elements by the specific X-Ray spectrum which they were stimulated to emit. X-Ray microscopes were invented in 1948 (Kirkpatrick, Scientific American, March 1949, "The X-Ray Microscope").

Most early X-Ray devices were powered by interruptive induction coil discharges (Hittorf, Crookes, Lenard). Others employed static electric machines (Pupin, Morton, Rice). Others employed potent combinations of these in order to "pump" the target (Shallenberger). X-Ray tubes of this kind were eventually used to inspect steel plates and the quality of plate-steel welds, a prodigious source of penetrating energy. Multimillion volt X-Ray beam systems had already begun to make their appearance before the end of World War II. These systems later augmented the use of particle accelerators in nuclear studies.

2.4 BURST X-RAY BEAMS

Employed to disrupt the normal stability of material nuclei, it was learned that the bombardment of elements by such X-Ray intensities produced both new radioactive isotopes and an assortment of strange phenomena. The particle accelerators, themselves outgrowths of Lenard designs, were studied with respect to their ability in producing more penetrating and completely unexpected ray species. Used in combination however, the effects on matter were completely unexpected. The concept of producing a "cathode ray magnifying glass" became the topic of sardonic intrigue by those intent on preparing extraordinary weapons. By World War I there were several such systems which considered the deliberate and hideous use of X-Rays on the battlefield.

The possible military use of these beams was a statistical certainty. The employment of highpower RADAR beacons as experimental weapons systems had its proven effectiveness, numerous accounts tell of RADAR "accidents" by which the deadly effects of short time exposure to highpower microwaves was first realized. Nor have these reports stopped with the end of the Second World War. One yet hears continual accounts of such accidents, deaths occurring from exposures to 1 or 2 second exposures in line of fire with multigigawatt pulsed beams. These accidents are seldom reported as such, and do not require close range exposure. Both RADAR and X-Ray packages had their inherent limits based solely upon size and power requirements. X-Ray packages would yield more potent results, but smaller systems had to be developed.

X-Ray beam devices could never operate in continuous mode, the necessary power being far too excessive. But sudden X-Ray "burst" designs would be effective and portable, the requirements consider-

ably diminished by the form of ray delivery. Burst X-Ray systems could store their primary power in capacitor banks, the support voltage being maintained by diesel-powered dynamos. The sudden release of current through a properly constructed Lenard Tube would produce a devastating energy blast in any desired direction. But such "X-Ray Flashlamps" had their inherent faults. Problematic in the use of such configurations was the non-coherent nature of such X-Ray emissions. Whether composed of particles or of waves, these beams could not maintain their intended collimations for very long distances. Lethal, yes. But capable of striking with devastating instant force from the safety of a great distance...no.

There were numerous natural obstructions whereby X-Ray bursts became less powerful with increasing distance in air. Atmospheric components greatly absorbed the X-Ray energy, gradually degenerating the beam force into highwattage thermal energy. The launching of energetic beamrays such as these could not be camouflaged. The X-Ray flashlamp produced a telltale signature, a characteristic plasma flare by which the cannon assembly was all too easily targeted. In addition, this flare did not easily or quickly disperse with time, building an ionization cloud which made the continued use of the weapon increasingly less effective with battle time in a fixed location. There is no objection in hoisting such a system aloft, however. Such a system would have represented a lethal force from a moving height. Indeed we have secured several different detector systems which, in the absence of their powerful and penetrating companion X-Ray or Gamma Ray searchlight components, reveal an early use during and after World War II.

In the Cold War years, attempts were made to collimate burst X-Ray beams as close to the ray source as possible. It was empirically found that very intense radiations could be obtained by bombarding radioactive targets, some inventors combined electrical discharge systems (in the manner of Lenard) with the use of radioactive beta-emitting targets. The production of exceedingly intense X-Ray bursts was secured by the application of low-power DC arcs on radioactive anode windows. Intense X-Rays were thus derived from comparatively small device packages. These systems were so compact and articulately controlled that they, while intended for weapons applications, also became the core of signalling modulators: it having been discovered that varying bombardment of radioactive materials by electrical discharges resulted in the production of varying radiation streams. Weapons designers foresaw the potential use of Lenard systems on the battlefield, using radioactive matter as the initial bursting source of radiation. Utilizing small capacitor storage units, such devices applied sudden arc currents to beta-radioactive sources. The radiant outputs from these was then applied to special radioactive alloy anode windows. The resultant deadly yield provided short and intense X-Ray blasts from a compact field unit.

2.5 EXPLOSIVE BEAMS

Radioactive metals have been alloyed with heavy metals (tungsten, platinum, lead) to produce a remarkable and constant radiant yield. With radiant emissions constantly moving through such an alloy, the optical properties of solid geometry best direct the radiant energy. Cast in specific shapes and used as target matter for electron pulse discharges, such an anode considerably extends the Lenard principle (Reiffel, patent). Despite the great variation in shaped cathodic beams, designers found the task of producing a strictly collimated beam quite difficult. The target-burst variation produced high thermal energy particles or radiation hybrids, whose group volume rapidly expanded with increasing distance from their source. The penetration effects of such bursts were severely hampered as a result of this natural expansion factor. While such systems worked well in space, their efficiency through air was completely deranged.

In air, these beams caused lightning like discharges which negatively modified the burst volume. These discharges represented a degeneration of the intended radiation burst, drawing away much of the burst power at the very instant of application. Emerging from the device barrel, the initial power was dramatically decreased on impact with air. In addition, the accurate direction of the burst could not be completely

insured. Spurious atmospheric discharges so increased the turbidity of the beam that its course required statistical targeting. The need was for a coherent X-Ray LASER, one whose emerging beam was so intensely collimated that it could "bleach" the atmosphere, creating for itself a conductive path.

The use of empirically developed multilayer perforation screens, "multiple pinhole cameras", achieved the collimation of photons far too energetic for ordinary material lenses. The radiation from a point Gamma Ray source (Cobalt-60) is collimated into a powerful beam which maintains its parallel format for great distances (Gschleidlen, patent). Such collimators relied on the rectilinear propagation of the X and Gamma Rays; energies which are neither stopped by most obstructions, nor thus deviated from their original course. Designers of beamray weapons and communications systems made the best use of these rayic properties, a brute force parallel beam method which was greatly analogous to lighthouse beacons. Such systems lost much of their initial energy before passing through the multiple baffles of the collimator itself. Ultimately, these pinhole camera systems failed from inherent problems of fundamental incoherence from the source itself, an intriguing engineering problem requiring the discovery of new phenomena for its solution.

The kinetic and thermal methods for releasing coherent radiations relied upon energetic impacts: electron shock phenomena in various elements. Such shock effects produced transitions in the orbitals of target matter which were not thoroughly understood. Had they been better analyzed from the work of von Laue on X-Ray diffraction, then investigators could much sooner have engaged the theoretical dialogue necessary for the design of coherent ray emitters. The instantaneous stimulation of quantum states, within the locus of a tiny point, often brought surprisingly "monochromatic" and highly organized radiations. Though chaotic in generation mode, these superthermal impacts produced intense quantum "avalanches" which in every way behaved as coherent emitters. This behavior may be comprehended in the following manner. The plasma point grows in quantum-gated steps, gathering photons of the same energy in locked-phase with each of its expansive steps. In an infinitesimal increment of time, the plasma reaches its maximum phased absorption of available photons, and bursts forth. A defined kind of coherence is thus derived from the very sharp and highly focussed impact of appropriate target matter.

Long before both MASER and LASER technology emerged, a bizarre system explored the use of brilliant light sources for the release of Hard Ultraviolet, Hard X and Gamma Radiation. The existence of small fractional kiloton nuclear warheads was never imagined. Nevertheless, this system used such warheads for the production of super powerful light beams (De Ment, patent). Long containment pipes provided sufficient time for the multiterrawatt nuclear stimulated radiance to be reflected out of the vessel before the entire device was consumed by the blast. Producing very large diameter beams of inconceivably huge radiant output, the inventor referred to the resultant emissions as CAL (Clear Atomic Light).

Equipped with target windows of any required "fluorescent material", the primary developer of these CAL weapons stated it possible to release any desired particle or ray species through nuclear radiant illumination. One could thus easily release hard X or Gamma Ray blasts, itself an exotic Lenard Tube of military dimensions. It is not at all difficult to recognize that this system can easily be inverted in any orientation, applying its lethal beamrays toward any target point. Scaled up in dimensions, such a device could produce a radiant beam of any desired diameter. Rays such as these were tested for their ability to incinerate objects. This system was, in all probability, considered for deployment and placement in orbit.

Before the development of far better and more pernicious radiation weapons, this CAL beam weapon had no equal. Its declassification in 1973 occurs some 15 years after its testing in coincidence with Project Plowshare, a "peacetime" use of nuclear weaponry. These experimental weapons were part of PROJECT DEFENDER, the original Star Wars Defense Initiative of President Eisenhower. This Project investigated the use of directed hot nuclear plasmas (PROJECT CASABA), high energy particles (PROJECT HOWITZER), and primary experimentation with X and Gamma Ray LASERS. It has been suggested that this primary Defense Initiative was abandoned in 1960. The deployment of nuclear capable ICBM systems

offered the more practical and accessible approach to the defense needs of the NAO.

The SDI modification of the CAL device appeared as several highly publicized X and Gamma Ray LASERS. The radiation blast of a fractional kiloton warhead is used to produce highly directed gamma ray beams of immeasurable potential. The warhead is poised in a tanklike structure whose periphery is studded with special "Reiffel-type" directive rods, radioactive alloys. Here was an application of an effect discovered by Rudolph Mossbauer, and which we must thoroughly discuss in the next section. Useful only in the brief time interval before itself being incinerated, the detonated warhead pumps the LASER Rods with nuclear light. The light is saturated with X and Gamma Radiation, a suitable, saturating flash of energy to stimulate lasing action.

Surrounding the first form of the Nuclear LASER with some 50 or more of these high density Reiffel Rods, one is able to produce an enormous diameter X beamray for the specific purpose of destroying missiles or cities alike. The length of the rods employed determines the amplification factor. In one model, the rods each point toward a single target. In later press releases, Teller described an embodiment in which each Reiffel Rod was capable of being individually aimed. Capable of targeting specific locations, this second form of the deadly device would effectively incinerate all life at each of its prime focal points. Hailed by Teller as the "perfection" of nuclear art, these horrifying third generation weapons captivated and focussed the fears of humanity once again. Teller was once again in the spotlight. The final weapons "contributions" of Dr. Edvard Teller to our world was in no way imaginative or decisive. The technology represents a degenerate consciousness, one which has repeatedly been occulted by a far more incisive biodynamic technology.

The Defense Nuclear Agency conducts some 20 underground test shots yearly, a practice which has consistently tested new weapons since its inception in 1963. The Nuclear LASER systems employed similar methods as those of PROJECT DEFENDER, where CAL systems were tested in very deep horizontal and vertical chambers. Code-named DIABLO HAWK, tests on a nuclear pumped Krypton Fluoride LASER was conducted on 13 September 1978. Prior to the over-emphasized Reagan "Star Wars" speech, a series of tests had already demonstrated the new weaponry. Indeed, the declassified patents reveal that superior beamray weapons had already existed. Long before the DAUPHIN Nuclear LASER test, which occurred on 14 November 1980, coherent beamray weapons had been tested and abandoned. Several more highly classified test shots took place before and after the Reagan speech, a revealing configuration of secret confidences and bold press releases. The ROMANO test occurred in December 1983, having been both preceded and followed by other shots.

Somehow believing himself suffused with the message which the world awaited, Teller hoped to excite the public to new ideals with his announcements. perhaps he believed that the nation of beleaguered working class citizens needed his words to have hope. In atypical excited monologue, Teller publically foisted these systems as the "ideal nuclear weapon". Lacking all of the hazards which made tactical nuclear explosives impractical to their users, these Nuclear X-LASERS were said capable of performing their killing task with "highest efficiency". Made to incinerate only living things in the beamray, such weaponry would permit the instant occupation of lands so destroyed. No radioactive signature would remain in the stones or dust below. There would be no fallout, no debris. The beamray method would kill and carbonize all living matter, while leaving the "real estate" intact.

Manifesting only the perfection of his own insensitivity, his revealing rhetoric once again exposed the essential character of those seduced by wealth and vainglory. Power, that given by superior command, explodes such personalities beyond all sense of their own very human proportion or self-worth. Teller found himself a familiar media personality, somehow again imagining himself the national hero of the hour. It had been quite long since the spotlight brought him into the public eye. The hydrogen bomb was his first "present" to the world. Nuclear LASERS was his chance to again surprise the world. Those who recognized the real significance of these rare press conferences viewed a man, completely incapable of

recognizing his thoroughly alienated condition. Here was seen the true effect and reward of power, that which superior command delegates to those whom it uses. Demonstrating a bizarre hubris, Teller became the intended target of public reaction, being again a mere tool for the private dictates of his shadow masters. Exposure to the technology of death alters both perspective and consciousness, evidenced when Teller referred to NUCLEAR beamray weapons as "humane" and "effective". Perhaps he needed to look deep into the faces of those for whom these designs had been prepared before stepping into the spotlights for awards.

2.6 HIGHPOWER LASER PULSE

The nuclear flash method resulted in the production of staggering coherent bursts, but was unable to maintain this production for periods longer than the self-incineration interval. X-Ray modulation was quite difficult to obtain. The electrical burst method provided intense beamrays, but required the construction and maintenance of large installations. To be sure, the requisite elemental media capable of being stimulated to X and Gamma Ray quantum states were not difficult to compose. But the critically small discharge intervals at high power could not be obtained through electrical discharge alone. The designers gradually shifted their emphasis from electrical discharge initiations, and began to explore the use of high-power LASER discharges as the primary burst source. LASER bursts could be exceedingly powerful, while lasting for a nanosecond or less. Other difficulties lay in finding the requisite optical cavities to reflect and intensify the radiations. The very fact that X-Rays permeated matter rather completely precluded the use of material lenses or the optical geometries of materials for their modification. Other phenomena had first to be discovered before realistic X-Ray optical cavities could be configured.

The directed release of X-Rays through shock-vaporized metal wires was reexplored (Wood, patent). The discovery that sudden progressive vaporization along lengths of extremely fine wire could produce a coherent X-Ray burst occupied the intense development of several other research groups. But a more continuous form of weaponry was desired. To this end, several strange composite power systems were employed. Revealing new interactive phenomena, the use of small linear accelerators to pump an X or Gamma Ray plasma has been demonstrated with success (Viecelli, Sprangle, patents). Uncommon energy transformations occur when counterflowing beams of accelerated electrons and LASER light are admixed together. These units can be remarkably compact in design, systems which would have no problem operating in the frigid darkness of a deep orbital station. Others reexplored the Lenard tube and its projective potentials. Modern Lenard systems used LASER-targeted multiple windows, an attempt to build up the power of a single burst by successive bombardments. In this shock-layer method were also discovered strange quasi-optical effects by which emerging monochromatic X-Ray beams seemed better collimated and better able to maintain their collimated condition for greater distances. The use of focussed arc discharges on appropriately layered metal targets, combinations whose radiant yield comprised both the X and Gamma Ray spectrum, were developed.

X-Ray quantum yields were directly related to the metal foil layers utilized as "ammunition". Outputs from these "exploding foil" devices were decidedly coherent, a process involving the progressive release of X-Rays through the expansion of successive metal plasma layers. One such exploding foil system employed selenium and tantalum (London, patent). For a short time maintaining their relative boundaries, these plasmas absorbed primary LASER energy while converting it into X-Rays. The layers formed an exotic cavity which, while incapable of reflecting the X-rays, organized a coherent structure for a very short time. Once thus organized, the X-Ray beam would burst along the axis determined by the initiating LASER pulse. Alternately layered targets of very specific high and low density metals are especially potent coherent X-Ray emitters. In these embodiments, gargantuan infrared LASER pulses were focussed into

the same layered foil composites, propelling a progressive coherent population of X-Ray photons toward a fixed focus (Mallozzi, patent). Exploding foil systems have gradually evolved into detonators, termed "slappers". These devices play a dramatic role in the Radiation Technologies responsible for Gamma Bombs. Special multilayers of metal foils and radionuclides compose slapper detonators. The intense gamma bursts obtained from these, effectively trigger the explosive core of Gamma Bombs.

Analogues to the exploding foil techniques, the use of layered chemical lasant media have been explored. Water soluble sulfates of copper, iron, and zinc have been wedged between microscope slides, producing gel targets. These are vaporized by LASER burst techniques, and is successful in producing very powerful X-Lasant plasmas (Kepros, patent). Other similar embodiments combined varied elements in closely packed layers. The use of very thin sodium-carbon-neon layers has successfully produced coherent X-Ray beams (Cochran, patent). Such lasant media are systems requiring constant cartridge replacement. The layered weapons composites are incinerated with each firing, an exotic "ammunition" having deadly output. Gas analogues of fine-wire vapor systems use capillaries of high pressure X-Lasant gases, continuously activated by focussed LASER energy (Tomie, patent). This system resembles Teslian designs. When speaking of "teleforce", Tesla described his use of open-ended gas jets to surround his high tension terminals, this being principle means for the production of "intense threadlike beams of true force".

The use of timed LASER pulses, adding newer and hotter boundary layers to a primary plasma body has produced long lasting X-Lasing action. The successive vaporization of additional lasant matter from a multilayered metal foil, a process known as "gain-pulse spiking", continually adds new lasant plasma layers to a growing column (Kepros, patent). This progressive addition of hot layers intensifies the resultant effects by increasing both the plasma density and its effective lasing time (Charatis, patent). But this method, while finding weapons utility for small cross section strikes, does not produce enough power for the targeting of battleships or installations. By developing very dense lasant volumes which last for long time periods, metal-gas systems are capable of greater X-Ray outputs. Systems such as these, deadly weapons, have produced incredibly coherent X-Radiation while operating in the multi-Terrawatt level. The development of these began with the use of chemical plasmas in continuous beam LASERS. While many researchers spend time discovering new quantum transitions for the production of excessively succinct X-Ray spectra, others concentrated effort on the generation of excessive power. Maintenance of higher density lasant volume for longer time intervals provoked the design of large volume, long duty X-LASERS.

2.7 X-RAY LASERS

Chemical-gas X-LASERS use liquid fuels in burn chambers to produce coherent extreme Ultraviolet (EUV) to soft X-Radiation (Wang, patent). Others activate corrosive gas-metal plasmas by LASER bursts. Nitrogen-Fluorine, Cadmium-Zinc, Sodium-Neon, Vanadium-Titanium, Carbon-Manganese, Aluminum-Erbium, and Silicon-Dysprosium are some of the endless combinations. Exotic gas and chemical-gas media have formed the heart of EXCIMER research (Tomiyasu, Meinzer, Nighan, patents). These systems have employed fluorides of argon, xenon, neon, and krypton to excite extreme quantum transitions in various hard ultraviolet and hard X-Ray spectra.

The use of dense volume metal vapors and lasant media have produced the most powerful X-LASERS to date. High amperage electrical discharges are combined with highpower optical LASER pulses in order to produce frighteningly powerful X and Gamma Ray emissions. Eutectic alloys of lowest possible melting points are employed in certain X-LASERS. Boron-Nickel-Platinum and Gold-Silicon are some of these exotic X-Lasant blends which are made to melt and rapidly become a vapor when electrically activated. The high amperage electrodischarge converts portions of the eutectic solid into liquid, and the liquid into a dense plasma gas. Continued electrodischarge raises the plasma into excessively stimulated quantum

states which, by highpulse LASER excitations, produce the intensely penetrating X and Gamma Rays for which they are so highly prized. These "Z-Pinch" plasma devices fire beams easily capable of melting clean holes directly through thick walls of metal and stone. Those who direct the development of these weapons are rarely concerned with disclosing the secrets germane to their actual reconstruction, a curious arrogance which betrays far too many cryptic elements. The inner workings of bureaucracy cannot hide the motives of those who have rushed into the making of these superior weapons. Fulfilling the designs outlined in the early RAND proposals, a great number of X and Gamma LASERS can be placed in orbit, the perfect weapons station.

The ability of X-Rays most noticed by its early observers was its strange, inherent ability to pass through most substances. While representing its major distinguishing characteristic, this attribute makes the task of developing a true photon cavity resonator for X-Rays virtually impossible. All of the former designs which have been thus far mentioned were systems which developed travelling beams of coherent X-Rays. None employed resonant cavity intensification of radiant emissions, a feature which severely limited their overall efficiency. All of the systems which used travelling shockwave methods for gathering monochromatic photon populations were incapable of employing optical cavities, those normally use in raising visible light intensities in LASER arrays.

By comparison with the burst technologies, those techniques which make coherent X-LASERS possible, true optical LASER action permits enormous photon gathering efficiency over longer time periods. It is routinely possible to produce Terrawatt optical beams because of mirrors. Optical lasing action occurs as we feed a lasant medium with external energy. Raised to critical transitions, the continual cascade of photons harvests vast yields in an organized "coherent" manner. Von Laue (1906) discovered that rock salt and other crystals have defined effect on X-Ray beams. But X-Ray light is not appreciably refracted by ordinary lenses. They require special multiple vanes and pinhole composites, as revealed in a great variety of X-Ray pinhole cameras (Andrews, patent). Magnesium Fluoride or Lithium Fluoride windows have been used as hard Ultraviolet transmission windows. X-Ray mirrors have been developed for use in the soft X-spectrum.

Flat halide reflecting cavities, partially reflective X-Ray mirrors, have been composed of salts and mineral crystals. But having a maximum reflectivity of 50% or less, these can provide optical resonances only for a few "passes". These were designed for use in early X-LASERS, but did not allow sufficient amplification by continuous reflection. Spontaneous amplification occurs only with successive passes through the lasant medium. As X-Ray wavelets and particles rise beyond a given threshold, the now intense beams cannot be stopped by the crystal mirrors. The few "passes" made while the photons permeate their lasant medium produce a minor amplification until the escape point is reached. Until the discovery of true Gamma Ray lasing phenomena, all weapons research moved toward the development of X-Ray LASERS. Through the inherent limits of the art, attentions were concentrated on burst-pulse technologies; major design representatives being contained within this collection.

By developing far superior weaponry, nuclear warheads would join the mace, axe, or crossbow of heraldry as antiques. The later history of the Cold War came to a close with the development of working beamray weapons. The advent of SDI marked the new era. Warfare had developed to the place where electrically slaved beamray systems had effectively rendered all nuclear warheads obsolete. Electron LASERS marked a rare advance in this progressive campaign to rid the world of nuclear horror. Requiring large stationary installations, linear electron accelerators were combined with MHD technology to produce the most powerful LASER regime. Free Electron LASERS (FEL) employed a number of fundamental phenomena to produce frighteningly powerful pure light energies approaching the optoexplosive Clear Atomic Light technique. The development of ELECTRON LASERS utilized the qualities of mammoth single burst electron bunches and their behavior in magnetic fields. High density terrawatt electron bursts were accelerated in hard vacuum toward a static array of powerful magnets. This array, stacks of alternate

magnetic poles, was termed a "wiggler".

Clumped electron bursts were directed through the "wiggler", each burst group being forced to vibrate in perpendicular directions to its direction of travel. These systems produced radiant blasts of photon energy strictly equal to the velocity of the electron burst. Cerenkov radiation produced by this burst method, the FEL method successfully released inordinately intense light energies of very specific frequency. Experiments with these weapons systems were conducted throughout the SDI period, where huge hangar-sized electron accelerators beamed their "wiggled" coherent emissions toward...and shockingly through thick steel plates. The resultant holes were smooth edged and excessively large in diameter, penetrations for which two solid feet of steel was virtually like tinder. Reflected from large mirrors, this penetrating light vaporized high velocity moving targets. FEL technology was adaptive to the production of both X and Gamma Beamrays of terrifying potential. The simple imposition of special windows easily converting the device into a superpowerful Lenard System. These target windows were composed of alternate heavy metal layers, sometimes including radioactive isotopes. The searing quasicoherent Gamma Ray energies emitted by these weapons represented the literal release of radiance equal to small yield nuclear warheads.

Since the radiant emissions of these FEL systems were available by the push of a command switch, they represented a superior potential to any nuclear weapons: lethal radiation without the devastating blast and its concomitant contamination problems. To the perverse minds which devise such technology, these were elegant solutions. None of these weapons violated any of the progressively stringent international space laws, laws which prohibited the placement of hazardous fissionable systems in orbit. The possession of superior weapons systems now permitted the space deployment of an hybrid weapons host...an aerial armada which was not nuclear until empowered electrically. Radiation weaponry is Electronuclear weaponry, systems which release nuclear fireball radiations on command. Because they are not normally radioactive in the fissionable sense, electronuclear weapons do not legally violate the existing terms of space weapons treaties...they cleverly violate notions of nuclear energy in the weapons potential. Becoming operative at the flick of a switch, these weapons represent potentially more of a threat than a single strike nuclear warhead. Any single electronuclear weapon can be fired repeatedly, the equivalent radiant firepower of several warheads.

It is ironic that Dr. Nikola Tesla engaged the military in dialogue concerning the use of his Very Special Radiations for the defense of his adopted nation. This technology, all too curiously, seemed not to attract the least attention of existing military branches. Intent on developing a nuclear arsenal, military advisement betrayed a singular lack of foresight on behalf of the NAO (see parent text). It was not until the death of Tesla that military agents broke into his New Yorker Hotel rooms; scouring both the penthouse where he lived, and his penthouse laboratory. Secretaries reported that his private safes had been opened, the contents completely removed. Questions were asked concerning his several widely scattered trunks, repositories of completed works on a great variety of topics germane to Aether Physics and Aether Technology. Those who examined the material later assessed the designs as "containing nothing suggestive of a weapons system", conducting their analysis of course from the staunch viewpoint of a more conventional understanding.

SECTION 3

RADIATION COMMUNICATIONS SYSTEMS

3.1 EARLY RADIANT COMMUNICATORS

A wide variety of radiation modulators precede the development of high penetration particle and wavelet technologies. The concept of communicating on a lightbeam was conceived and developed by a great number of inventors before the end of the Nineteenth Century. Photophones and Radiophones, as they were termed, used a variety of means by which beamrays of light were modulated by the human voice (Bell, Tainter). It was thus possible to establish point-to-point vocal communications along a vibrating lightbeam. This method found a tremendous appeal among maritime veterans and military personnel. When once it was established that both infrared and ultraviolet rays could afford a "secret" channel of communications, military agencies took greater personal interest in the technology (Case, Zickler, Coblentz).

The early development of darkray communications systems preceded the development of MASER and LASER technologies. There were ray communications systems already in development before the end of the Nineteenth Century. The first of these systems were capable of telegraphing code along a stuttering aether beamray. These were eventually replaced by vocal modulators, the rays acting as penetrating signalling agents. Again, one name stands out in this unexpected application of strange new energies: Nikola Tesla. His pioneering venture. His invention of vacuum-projected Radiant Energy signalling systems was the direct result of familiarity with the mysterious and powerful characteristics of emanations which he alone seemed able to obtain. The energetic darkrays from his tubes were capable of penetrating materials without being obstructed or deformed. The rays were therefore wonderfully suited for the establishment of a superior form of communications. Teslian very special radiation represented a coherent portion of an ambient medium which filled all space. It was therefore capable of travelling long distances directly through intervening obstructions without appreciable loss.

Dr. Tesla first experimented with the use of Radiant Energy beamrays specifically for use in communications, and developed finished systems toward those ends (patents 685.957 and 985.958). Tesla also pioneered the development of selenium crystal detectors of these special darkrays, the very first demodulators of their kind (patent 685.954 and 685.956). These demonstrations

proved that signal exchange could effortlessly be established with the smallest of devices between any two points. Exchange was not predicated n conditions of position, distance, intervening obstacles, or meteorological conditions. Marconi Wave Radio was plagued with all these flaws. The technology of Tesla was not easily duplicated by most of his contemporaries. Lacking sufficient understanding of his simple, but profound methods, most modern experimenters have again been unable to achieve the claimed effects. Only Eric Dollard has successfully duplicated several of the Radiant Energy communications effects. There certainly remains much more to rediscover.

But once the idea was enunciated by Dr. Tesla, several experimenters began realizing the feasibility and potential of systems employing penetrating radiations. But "interpretation" abounds in the scientific realms. When a phenomenon cannot obtained, it is either rejected or interpreted. Unable to achieve the Teslian results, several experimenters interpreted Radiant Energy Technology in terms of X and other more energetic Rays. But several factors prevented most investigators from realizing the inherent potential of X and Gamma Rays for either power transmission or signalling. The excessive fame and mysterious nature of the X-Rays literally blinded the eyes of experimenters for a long time, and few were able to grasp the use of these rays. For most academes and experimenters, X-Rays were totally unlike light. There were few materials with which the X-Rays would interact at all. X-Rays seemed to represent an ultimate reality of

space which held most experimenters in awe. Recall that X-Rays had been viewed as a harmless manifestation of light: untenable, insensible, and ephemeral. The X-Rays were equated by the academes with aether itself. The excessive academic publicity, which failed to credit Sir William Crookes with the discover, had failed to grasp what Dr. Tesla later claimed concerning aether ad X-Rays. In his numerous articles and lectures, Dr. Tesla repeatedly affirmed that X-Rays were a distinct by-product of aether stream bombardment in metals.

According to Tesla, X-Rays were not fundamental in nature. X-Rays were a far more convoluted "wavelet energy": large vortices in the aether, but not rarefied aether itself. Tesla came to recognize that the highly energetic and purified streams which he had obtained were not the same "X-Rays" as those investigated by the others. His "very special radiation" was composed of a purified aether stream, a ray of ultimate particles. These ultimate particles comprised the Radiant Energy with which he was principally concerned and on which his technology completely depended. The excessive familiarity with the study granted Dr. Tesla a confidence which was soon hated by many of his contemporaries. Notable among these was his own countryman, Michael Pupin, who sought every opportunity to slander and vilify the very name of Tesla. In several lecture presentations, Pupin incited his students to make loud and mocking noises whenever Tesla made a statement; an interaction which Tesla did not refrain from deriding.

Pupin claimed he had preceded Tesla in the development of X-Ray photography, while Tesla simple cited Crookes as the true discoverer of X-Rays and the originator of both the fluorescent and photographic X-Ray process. This was in fact the historical precedent which most chose to ignore. While heaping their praise on Roentgen, the media-launched fame diverted attention from Dr. Crookes. He had been the object of derision far too long, the twinkling little man who used his globes to actively searched for "ectoplasms". Most of his petty flatterers, young members of the Royal Society, wished him completely out of the scientific world...if not out of the world altogether. He was an ancient standard, a noisome reminder that Victorian Science produced far more revolutionary discoveries and technologies than their theoretics could provide. Tesla was viewed in the very same light, a derisive association which Tesla gladly accepted. Tesla was in fact the very first to cite the damaging power of both Lenard and X-Rays. Tesla made it clear that the aether rays, which he had discovered, were capable of permeating matter because they were in such a rarefied condition.

The hazards of exposure to such "large complexes" and "aether vortices" could not be enough overstated. Being such "large energetic complexes", the X-Rays were incapable of truly passing through tissues without damaging them. Their vortexian nature passed through delicate tissue like winding screws, tugging and dragging biological materials to pieces. Despite the mounting derision concerning his statements on X-Rays, the bad news concerning dark radiations soon became an unbreached barrier. Severely overexposed to hard X-Rays, Lenard Rays, and the Gamma emissions of radionuclides, a great many experimenters suffered from strange burns and terribly degenerative illnesses. X-Ray energies, though invisible, insensible, and untenable, were recognized as lethal agencies. It was just as Tesla had stated.

For private experimenters, the subject of X-Rays was first shunned, then feared, and then excluded in that order. The gradual rejection of studies in Radiation Science overcame the greater portion of private experimenters. Thoroughly occupied with the exploration of an emerging Marconi Wave Radio and its application, the scientific community typically shifted its gears and fled the former quest. Only the industrial development of commercial X-Ray Technology continued, a study virtually dominated by large corporate conglomerates such as General Electric. This industry-monopolized examination of X-Ray energies did not encompass the kind of creative vision which early characterized the energetic experimenters of 1896. Industry focussed on single objectives for mundane applications, the harnessing of spectacular energies as a mere tool toward the banal pursuit of corporate supremacy. The large million-volt X-Ray systems which were developed by Morgan-owned General Electric Company, were applied to the skiatographic examination of steel welds.

It had been popularly believed that the otherwise mysterious energy had been conquered by Industry, a notion which conveniently helped to privatize X-Rays and Radiation Technology among corporations. But the inventive and visionary pursuits of only the most bold researchers successfully developed X-Ray and radiation technology far beyond these boring applications. It was recalled that several strange phenomena had been observed by the first X-Ray experimenters. A host of energetic interactions and transformations between X-Rays and conventional laboratory apparatus had been collated during the period of intense private research. An incredibly wide range of Ray-electric and Ray-fluorescent phenomena captured the attention of researchers whose minds searched for new technological innovations.

In the electrical interactions, X-Rays could discharge and even modulate electrostatic loads (Robb, Thomson, Gerchun, Borgmann, Koch). X-Rays could easily charge neutral bodies (Righi, Minchin). X-Rays destroyed the contact potential of dissimilar metals (Murray). X-Rays modulated flames telephonically (Edison). X-Rays could be relayed by appropriated charged bodies and reflective angles (Rowland, Carmichael, Briggs, Thomson). They increased conductivity in selenium cells (Giltay, Haga). X-Rays were conducted most deeply through refrigerated objects (Edison, Roentgen, Trowbridge, Bleekrode). There were a host of distinct fluorescent phenomena which strongly suggested utility in exotic visual communications systems. X-Rays modified various chemical reactions (Goldstein, Lenard, Roentgen, Gifford, Meslan, Buquet, Gascard), and were capable of exposing photographic plates of special fluorescent combinations (Lumiere, Pupin, Swinton, Henry, Morton, Gifford). They stimulated fluorescence in non-electrified Geissler Tubes (Dufour). X-Rays produced variable fluorescence, strongly suggesting utility in a wide variety of signalling systems (Edison).

In each of these strong energetic transformations were perceived new possibilities for communicating both power currents, vocal signals, and visual images across vast distances. Where mountains and other intervening structures might otherwise occlude Wave Radio signal exchanges, Teslian aether-ray signals would simple pass through. Some explored the use of Deep Ultraviolet and Soft X-Rays for use in communications (Zickler, De Moura). Indeed, no essential difference existed between the use of Ultraviolet or X-Rays in radiophones, systems made to project and receive a stream of modulated high frequency light energy for longrange signalling. And there would have been more of these systems, but for the fear which accompanied the very mention of X-Rays. But in the discovery of these special energy transformative effects, interactive effects between X-rays and electrical systems, highly motivated private experimenters again found it possible to implement the strange rays in code-pulse radiophonic communications. These discoveries and embodiments remain largely unknown by the scientific community.

3.2 RADIANT MODULATORS

The advent of Marconi Wave Radio seemed to offer the greatest promise of longrange communications. This was especially true of Marconi Shortwave Radio, where field stations were easily established by the use of loop antennas. Military Wave Radio brought very effective countermeasures among the strongholds of the technologically adept. Wave Radio "jamming" technologies employed harmonically rich spark discharges and destroyed signal exchange for miles. Therefore a precedent had historically been set by the military implementation of a surprising assortment of invisible beamrays for communications. The highly privatized communications of maritime and landbased military forces had become part of the privatized intelligence technology arsenal. While the use of electroradiant (Tesla, De Moura), ultraviolet (Zickler) and infrared beams (Coblentz) during World War I established secretive communications links between dispersed field or ocean-going armed forces, several bizarre systems appeared which employed radiations not commonly considered usable in these venues. These X and Gamma Ray systems found application because of their generally unstoppable propagation mode, point-to-point radiant beams per-

mitting precise and unjammable communications.

Between the World Wars a very few undaunted Radiation Science experimenters tenaciously researched the varieties of radiant energies, with an aim toward developing a specific new technology. These pioneers established several true technological milestones, both for power transmission and communications arts. Certain of these pursuits produced true and powerful radiant energy receivers for the production of clean, pollution-free energy (Tesla, Hubbard, Moray, Ammon, Farnsworth). Some of these experimenters discovered the means for establishing longrange communications between impossibly obstructed points. Through a rare and truly mystifying discovery, Dr. Thomas Henry Moray found a means to listen in on remarkably distant locations. This small and compact device, which quickly became a matter of NRL classification during World War II, aimed small gas-filled tubes of radioisotopes at the ground. The reception of human dialogue, not the result of microphonic amplification, gave startling implications concerning the true nature of the biodynamic continuum and certain Gamma Rays.

By the beginning of World War II in Europe, several radiation inventions had already been tested. Because the energetic beams were endowed with natural ability to permeate most substances, X-Ray and Gamma Ray beacons were actively used to penetrate fog and the darkness of night, insuring the safety of both aircraft and maritime traffic ("Directing the Movements of Air and Marine Craft", Weber). Guidance systems were developed in quick successions, an exotic form of nightvision ("Ray Aviation Compass", Weber). These X-Ray activated systems found their more modern counterparts in Gamma Ray Technology ("Radiation Generator Providing Amplitude Modulation", Kaminskas).

The development of MASER technology was an application of molecular resonance phenomena to microwave technology, a completely novel approach to the amplification of superhigh frequency signals. MASER technology focussed the attentions of electronics engineers, less on the artificial production of electron populations, and more on natural frequency sources. The reason why the MASER approach was so radically different from klystron amplifier technology was that it utilized chemical vapors, naturally occurring generators of microwave energy. The very first MASER was demonstrated in Columbia University by the team of Townes, Gordon, and Zeiger (1954). The intensely coherent energy derived from a chaotic gas plasma surprised engineers, and stimulated designers to work toward the development of solid state MASERS. The very first such device was successfully demonstrated in Bell Laboratories by Feher, Scovil, and Seidel (1956). MASER technology was immediately applied to the first ECHO satellite transmissions. Robert DeGrassee handled MASER reception from ECHO I (1960), the highly amplified and clarified signals encouraging a veritable revolution in the drive toward the development of ever new "quantum" amplifiers.

Townes and Shawlow published theoretical discussions which described both the necessary parts and operational characteristics of an optical MASER in 1958. In this publication, the possibility of both infrared and visible light amplifying MASERS were considered. By 1960, Theodore Maiman test fired the first ruby crystal LASER. One gains a power advantage by the employment of special atomic populations, the applied light energy stimulating an enormous atomic population into cooperative resonance. The crystal LASER process is analogous to placing an iron rod in the core of an electromagnet. The same light energy becomes enormously amplified. In the case of the first ruby LASER, the crystal-poised Chromium atoms provided the cooperative cascade. The first ruby LASER was small, a system only a few centimeters in length and 0.5 centimeters in diameter. Nevertheless, it produced coherent red light through flash pumping action. The (0.3) millisecond burst delivered 10 kilowatts of coherent light energy.

While the development and proliferation of MASER technology was based on a need for greatly amplified microwave signals for communications, the development of LASER technology had no real base in communications arts whatsoever. The theoretical attributes of a powerful LASER system had defined applications only in weapons technology. As a weapon, the potential coherent energy of such a photon amplifier would be virtually unlimited. The first highpower crystal LASERS were produced by Raytheon.

The numerous demonstrations impacted the national and international mind with an intended slant on the weapons attributes of the intense light. This continual series of news releases, graphic demonstrations of LASER-perforated metal plates, taught the public that a new weapon had been secured. By employing atomic populations of naturally stimulated quantum states, populations whose normal ground levels were naturally stimulated, incredibly powerful crystal LASERS were developed.

It was known that the natural radioactive elements were already super saturated with free quanta. Self-stimulations flooded the Lanthanide series, where the addition of appropriate light energy could easily provoke a huge coherent avalanche of power. The appropriate mixtures of radionuclides produced a great and varied number of potent LASER spectra. Uranium-doped fluoride crystals formed the crystal core of one such powerful coherent infrared LASER. Flashlamps superpumped an already-stimulated uranium fluorescence, a system having an incredible power yield for its total size (Sorokin, patent). This radioactive LASER method was explored by others, whose efforts were directed toward the weapons development of coherent X-Radiation LASERS.

The potential advantage of a coherent light communications link was already discussed, especially among those whose interest lay primarily in the communications arts. The now divergent LASER technology required the simultaneous development of experimental weapons and communications systems. While flashlamp operation satisfied the early requirements of weapons contractors such as Raytheon, the communications requirement of Bell Laboratories called for a "continuous" lasing action.

The modulation of a coherent light beam would in no way differ from the designs formerly known as "photophones" and "radiophones". Photophones were devices which established vocal communications along a visible light beam. Radiophones were devices which exchanged vocal signals along an invisible light beam. This latter variety included the use of infrared (Coblentz) and hard Ultraviolet (Zickler). Each system failed to replace waveradio for a single reason. The inherent characteristic of light, by which its beams diverge across great distances, placed severe limits on the utility of radiophones. In time, several experimenters developed monochromatic beam radiophones, whose directed rays were curiously intense and which remained mysteriously parallel. This first recognition of coherent light provoked several decades of research toward the establishment of true coherent beam systems. The infrared MASER was the very first such system, the LASER the next.

It was not therefore unusual to recall that the very first gas-LASER was demonstrated in Bell Laboratories (1961) by Javan, Bennett, and Herriot. This system differed greatly from the ruby crystal LASER in that its operation was indeed continuous. The gas LASER depended not on the instantaneous high-intensity stimulations of flashlamps, but on the continuous stimulation of an electrical plasma. Here then was a means of producing coherent light directly from electrical power. Thereafter, the generation of a wide communications-worthy spectrum was pursued by a great number of experimenters. The patent by Gordon Gould is a veritable doctoral thesis on every conceivable aspect of the LASER art. Throughout the 20 year period which followed the very first LASER demonstration, a host of pulsed and continuous operation LASER systems flooded the Patent Archive. The Archive reveals the development of variant lasing media, media combinations, media symmetries, media stimulation modes, and the exploration of special spectral outputs.

The advent of the coherent beam technologies permitted the former infrared and ultraviolet radiophonic systems to operate over a vastly extended range with great clarity. Because coherent rays are rectilinear and intense, it was found possible to encrypt messages with a previously unknown density. The development of various LASER emissions, those including infrared and ultraviolet, were the deliberate design of communications developers. The inability of most visible light spectra to penetrate fog, clouds, and rain was solved to a large extent by selecting spectra with natural ability to pass through large volumes of water vapor. The development of continuous gas-LASERS produced an increased beam power with a concomitant ability to impress signals upon the beamray. This modulation potential was not new. But for LASERS,

formerly limited to highpower pulsed crystal apparatus, this ability to modulate LASER light gave a new and thrilling promise.

3.3 RADIATION CARRIERS

We have mentioned that the true and original models of all the Radiation Communications Systems are those several designs which were developed, demonstrated, and patented by Dr. Nikola Tesla (patent 685.958). Tesla Radiant Energy transceivers operated in an aetheric mode. The rarefied particle transmissions employed by Tesla, according to his assessment ultimately more refined than free electrons, effected a graphic vocal communications previously unknown in the wireless arts. In the Teslian communications systems, specialized vacuum globes and (later) long tubes replaced the aerial wires of waveradio. With these, Dr. Tesla was easily able to communicate across incredible distances with the most surprisingly compact transceivers. Military misinterpretations of Radiant Energy apparatus provoked research in X and Gamma Ray Technology, a field which could not live up to the legendary achievements of Tesla.

The misrepresentations concerning Teslian Technology motivated certain researchers to explore the use of X and Gamma Ray energies as communications carriers. It had been observed that fluctuating X-Ray streams produced fluctuating fluorescence in distant sensitive screens. This constituted a rather simple but complete form of a communications system. Photoelectric conversions between fluctuating X-Ray beams, fluorescent screens, and photosensitive cells had been implemented in one such system (Fua, patent). Whole image transfer systems anticipated the use of beamray projection through opaque filters, fluoroscopes providing the means for "decoding" the transmitted images. This technology, one which utilized a very special radiation, properly began with Nikola Tesla. Retrieved patents reveal that others, having misinterpreted his intentions, developed successful X and Gamma Ray image transfer systems.

When properly obtained, the energies were relatively monochromatic. X or Gamma Rays were possessed of such high energetic content that their projected divergence was not an impediment to the preliminary experiments. When properly projected, it was known that X-Ray beams did not diverge with great distance. The nature of these energies, however, was problematic. In the experiments which proposed the use of X-Ray signal carriers, the very nature of the radiation constituted grave personal hazard. Unless means were found for tightly maintaining the beamrays, or allowing the signal strengths to be negligible, both signalling parties would be at risk. Early X-Ray modulators could impress code or vocal signals upon the cathode supply of an ordinary Coolidge Tube, obtaining communications through a vibrating X-Ray stream. Telegraphy on an X-Ray beam!

These simple Coolidge Tube modulators projected their encoded signal beam to any one of a number of radiation-sensitive detectors. However primitive, the employment of a modulator and a distant detector forms a true communications system. Experimental investigations next sought the development of extremely collimated X and soft Gamma Ray beams which could be impressed with vocal signals. This posed an essential problem to engineers, the intensely penetrating rays not easily lending themselves to traditional modulation techniques. The theoretical modulation of any radiant energy requires control of the processes which generate those rays. But the valvular control of natural X and Gamma Ray emitters was not possible in these early years of development. Prior to 1962, there was no way to secure the modulated control of natural radioactive decay. The solution to this formidable challenge resulted in a remarkable series of embodiments.

The generation of primary carrier beams in both the X and Gamma Ray bands had been a developmental path having two solutions. The first involved the utilization of dangerous natural Gamma emitters, mechanical shutters, or mechanical vibrators. These systems, which required samples of Cobalt-60 or Strontium-90, were necessarily accompanied by excessive shielding requirements. Vocal-sensitive mechanical

modulators poised well shielded gamma emissives on delicate wire (DeLoraine and Goldstein, patent), on a delicate spring (Wanetick, patent), valved emissions from a radioisotope by varying a shutter window (London, patent), vibrated delicate pistons over emissive matter to impress audio fluctuations on emitted rays (Black, Hyde, patents), and flowed colloidal aluminum over X-Ray emissives to impress audio compressional waves on the radiation (Fanning, patent).

An ingenious method used beta-ray emitters in conjunction with electrical discharges. These beta-emissive substances were less dangerous, readily available, and more easily shielded than the gamma emitters themselves. Applying electrical modulations in directed streams toward beta-emissive targets in vacuum, experimenters obtained the powerful modulation of an intensely penetrating Gamma Ray stream. Signal-modulated electron streams bombarded various emissives to project graphically rich signals (Chope, Fua, Piekenbrock, patents). In this design theme, directed electron bombardment under modulated control was absorbed into beta-emissive material. The resultant X and Gamma radiation was completely modulated for certain pulsed-code and rudimentary vocal communications.

Gamma Rays from such systems were not the spurious emissions of a natural source, such as Cobalt-60 or Strontium-90. They were sources under modulated control, and could be utilized in audio beam transmissions. Bremsstrahlung modulators were effective and compact, but succeeded only in projecting incoherent "soft" gamma rays. While lacking the necessary coherence for long range, distortion-free communications, these components provided a step in the art. This electron-bombardment modulatory process found improvement in various downscaled weapons designs, those which also provided the attribute of coherence. Complex and delicate, these systems were soon replaced by an unexpected discovery. It proved to be one which totally revolutionized the art of radiation communications.

Whether produced through shutters, mechanical oscillators, or bombardment tubes...X and Gamma radiations can carry information. X and Gamma Ray fluctuations are varying columnar radiant densities which behave as virtual solid lines. These energetic carriers differ from the radiophonic use of infrared or ultraviolet light rays in both their material penetration depth and extreme rectilinearity. An emitted pencil of X or Gamma Rays undulates in density with time. The basic function of a mechanical modulator is to impress signal variations on penetrating X or Gamma radiant carriers. Mechanical modulation of either X or Gamma Rays is a largely inefficient process, better and more fundamental means were sought.

3.4 RADIATION DETECTORS

The contemporary science of radiant emissions and their detection, while properly having its origins in deepest antiquity, begins anew with the researches of Luigi Galvani (1777). Dr. Galvani observed an "atmosphere" of strange natural emanations, radiant currents of unknown species, projecting from large metal plates out into their surrounding space. His experiments highlighted the fact that physiological interception of these emanations resulted in powerful physiological effects. Contact with the plates in darkness produced effects which differed from those sensed with the plates in full sunlight. Elevated and insulated from the ground, these large plates of zinc or copper were able to produce remarkably thrilling currents; currents which have never found resolution in the electronic carrier theory. These physiotonic currents were never measured directly by either electrostatic or electromagnetic instruments, however sensitive.

Half a century later, Baron Karl von Reichenbach delved into the mystery, exposing large plates of silver, copper, iron, zinc to starlight, moonlight, sunlight, and the complete darkness of special chambers he had arranged for these purposes. Reichenbach discovered that an atypical current species flowed from these plates, observed in complete darkness as a luminous brush discharge of vivid coloration. Each element and chemical substance emanated a distinctive color and discharge form, evidence to the Baron

that a luminal energy was coursing throughout all matter in the world. This current species he termed "Odylle", or simply "Od". Odyllic currents were slow and permeating. They were completely different from currents produced by static machines, batteries, or small dynamos. On closer examination, Odylle currents more nearly resemble certain luminous energies produced by Sir William Crookes and Nikola Tesla. These white luminous currents also match the currents obtained by Stubblefield, Moray, and Reich.

The elusive quality of such energies direct our scientific attentions back to a previous Qualitative Science, where we are compelled to accept the fact that sensible forces do exist beyond the response of inertial measuring instruments. The existence of current species, those species first discerned through accessible subjective experience, demands a greater skeptical inquiry: one which accepts both the impotence of present measurement instruments, and the incompleteness of the highly restrictive and dogmatic force models presently accepted at the academic level.

Subjective discernment experiences energetic species which cannot easily be measured in inertial systems, and are distinct from the conventional electronic carriers on several accounts. The light-stimulated currents from metal plates, those investigated by Galvani and Baron von Reichenbach, were continually reexplored throughout the Victorian Epoch. As academes shifted their focus from less measurable qualitative currents to the measurable quantitative currents, a regime of Radionic Science developed among heretical academes and a large community of privateers. Radionic Science explored the potentials of the aetherial currents, developing a wide and astounding technological regime. Because academia ignored the findings, they were forced to consider only the gross measurable artifacts which have today become collated in Quantum Physics.

Interest in light, and its interactive effects within matter, again made a foray into human consciousness when the "photoelectrolytic effect" was discovered. E. Becquerel (1839) observed an increased current flow in a wetcell battery when one of the electrodes was brightly illuminated by sunshine. A great number of photoelectrolytic cells were subsequently developed to exploit this astounding find (Case, Garrison, Goldman, Brodsky). These cells converted light energy into electrical current, and varied the resistance of measuring circuits when exposed to light. Photoconduction in solid materials was discovered by Willoughby Smith in 1873. He utilized tiny rods of selenium as resistance elements in a bridge circuit. On being accidentally illuminated, these rods were found to greatly increase the total current flow in his sensitive bridge.

Selenium was a wonder metal, a brittle grey element which could not easily be worked. Sumner Tainter (1881), a technician who worked with A. G. Bell, discovered a means for drawing out selenium wire. This metallurgic feat permitted both Tainter and Bell to develop a "photophonic" system of communications. Beams of sunlight were modulated through highly reflective mica windows, projecting their vibrating beams toward a coil of fine selenium wire which Tainter had devised. The demodulation of this vibrating lightbeam produced an audible vocal signal in the earphone, an ordinary telephonic receiver. This was, as far as we yet know, the first modern instance in which telephonic signals were obtained through a lightbeam.

Heinrich Hertz discovered the photoejection of electrons when certain metals were exposed to ultraviolet light. Hallwachs (1888) soon closely investigated the phenomenon, employing ultraviolet sources, polished photoejective metals and fine-wire grids. Electrostatic fields were measured between these plate-grid structures in air. It was later learned by Augusto Righi (1888) that stacked combinations of these plates and grids were capable of greatly multiplying the normally small electrostatic field. Several premier Victorian experimenters began a fascinating exploration of photosensitivity. Preserving the Victorian truths which represent the heritage of accumulated centuries' empirical discovery, several researchers maintained their qualitative alliance. One such researcher, Dr Gustav Le Bon, revealed an unknown super-photoelectric effect in certain metals when exposed to sunlight. He produced artificial radioactivities in light elemental metals (magnesium, tin, zinc) under focussed sunlight. Anomalous in manifestation, these radioactivities actually exceeded the measured outputs of radium and thorium samples. The work of Dr. Le Bon strongly

inferred the existence of pre-electronic particles, a bombarding atmosphere capable of rendering radioactive certain appropriate elements.

It became therefore known that aluminum, magnesium, and zinc, each electropositive metals, produced the strongest photoelectric emissions. Two co-researchers, Elster and Geitel, discovered that amalgams of zinc and magnesium produced better photoelectric effects in air than the pure metals (1888). In 1889, they found that amalgams of sodium and potassium produced very strong photoelectric currents in air. These amalgams did not require ultraviolet rays, the stimulating sunlight having passed through a thick glass plate and produced a strong photosensitivity. This was the very first "photometric detector", a discovery which triggered a revolution in photoelectric research.

In 1890, Julius Elster and Hans Geitel patented a sodium amalgam vacuum tube. In this device, the photosensitive amalgam was hermetically sealed in glass. The globe was evacuated, the very first true phototube. Being easily stimulated by visible light alone, the device did not require special ultraviolet-permittive quartz windows. They soon discovered that hydride crystals of alkaline metals gave superior results to their amalgam globes. Their process used a stream of hydrogen gas over sodium or potassium film deposits, a bright colloidal surface being developed. Globes produced by this process (1912) were more than 100 orders in magnitude greater than all previous photoelectric cells. The invention of this special tube soon became a regime of specialized detectors, vacuum tubes capable of responding to and demodulating beams of radiant energy.

It became known that the placement of photovoltaic substances in either gas-filled or evacuated glass tubes greatly increased their response. Many experimenters hermetically sealed a variety of photosensitive materials, both elements and minerals, in glass tubes. These photosensitive detectors later comprised the heart of a number of subsequent discoveries in the Radiation Sciences, designs which ultimately found continual utility in Radiation Technology. A variety of photoelectric effects embodied a growing arsenal of sensitive detecting instruments (Case, Michelson, Hart, Goldman, et al). The early radiation detectors were specialized photosensitive materials, elements and minerals whose conductive response to incident radiation allowed them to function as transducers. Tesla both discloses and explains the use of selenium crystals as sensitive detectors of his pulsation rays (patents 685.954 and 685.956). This first use of photosensitive materials as detectors of pulsed and vocal-impressed Radiant Energy reveals a distinct difference in their Teslian use.

Supersensitive caesium-silver vacuum tubes were devised (de Boer, Teves), and later improved (Koller, Campbell, Asao, Suzuki). Photosensitive vacuum tubes employed thallium sulphide (Case), tellurium-selenium (Michelson), selenium-iodine (Hart), iron selenide-silver (Bergmann, Lange), molybdenum sulphide (Coblentz), potassium (Campbell), potassium-nickel (Knowles), potassium sulphide (Olpin), barium-silver (Case), barium-tungsten, barium-nickel (Lowry), cadmium (Griffith), sodium (Selenyi), (Becker), rubidium (Ives), and many others. These vacuum tubes were later referred to as "primary emission" tubes, a reference to the photoelectrons released from their sensitive metal plates when properly illuminated.

The chemical process of depositing sensitive photocathodic material often required the presence of inert gases within the tubes, processes which left gas traces despite subsequent evacuation. These residual gases actually strengthened the vacuum photoelectric effect, and experimenters found that the addition of a gaseous atmosphere enhanced the output currents of photosensitive materials. Investigators used hydrogen, helium, nitrogen, oxygen, and other gas-filled tubes (Mohler, Foote). Others tested the worth of neon, krypton and xenon in magnifying photosensitivity (G. Hertz). A new variety of photosensitive tubes demonstrated that phototarget materials flooded the gas with ejecta, a bombardment which resulted in an emission of secondary electrons. The bombardment products were reabsorbed from the gas, by the anode rod. These gas-metal interaction tubes produced greatly amplified currents.

Certain metals and gases were found to function best together, combinations which produced excessively strong secondary emissions. Any detected signal, however weak, could be raised by an articulate

physical process. Amplifiers of the photoelectric effect, these new gas-filled tubes produced strong photoelectric signals in response to the slightest incoming radiant energy. Experiments verified the use of multiple gas mixtures and photoemissive metals. Caesium layers on magnesium were immersed in a low-pressure atmosphere of neon-argon, a design which excelled all previous phototubes (Penning). Certain experimenters constructed composite tubes, by which photosensitivity was actually amplified through thermionic emission (Asada, Hagita, Geffeken, Richter).

Because so many experimenters misinterpreted the findings of Tesla, a subsequent use of early photoconductive materials as radiowave detectors flooded the literature. The waveradio phototube detector represented an anomaly which was never fully and properly addressed. Why any material sensitive to light photons should be capable of responding to electromagnetic waves was viewed only by a few. The old pre-Maxwellian concept that all radiant interactions were interactions in the Aether capably addressed this anomaly. One curious such design was able to detect radiostation transmissions by simply scanning the horizon with a special yard-long thermionic photomultiplier (McCullough). Misunderstood and curiously ignored, this compact system enabled military forces of the Second World War to determine the direction of enemy transmissions with unerring accuracy.

For a great variety of military and industrial functions, the amplification of weak incident radiation signals became a priority just before World War II. Phototube characteristics were studied with special attention toward the production of powerful photoelectric avalanches, an increase of output signal being greatly desired by certain agencies. During the Cold War, phototube technology reached an acme which is revealed only in the declassified patent records.. Multiple plate phototubes, analogues of the discharge devices produced by Righi, became a new focus. Photomultiplier tubes greatly advanced this pulse-code demodulation of radiation signals, employing the added noise potential given by radioisotopes under photoelectric bombardment. Military contractors provided their respective armed forces with special radiation detectors for a wide variety of applications.

No single researcher did more to utilize and perfect the photomultiplication effect than Dr. Philo Farnsworth, whose astounding designs revolutionized the electronic arts. Dr. Farnsworth choreographed the sum total of photoemissive technologies, by his masterful genius employing hitherto unknown geometries to produce his famed Multipactor Tube. A plethora of his designs exist, apparatus having anomalous efficiencies scarcely represented by our few bibliographic references. Reconfigured into radiant energy receivers and imaging systems, these deeply inspired devices literally "make visible that which is invisible"...thus the military "IATRON" advertisement states. It is a technology in which Dr. Farnsworth remains the premier visionary.

The numerous Farnsworth image amplifiers and image storing devices demonstrated enormous ability to amplify insignificantly small incident radiant signals. The Farnsworth Multipactors employ thoriated mirrors and caesium plates, and develop avalanche emissions by radioactive multiplication. This principle gradually became the adopted standard in a wide variety of radiation signal receivers, where input X and Gamma Rays were transformed in wavelength and magnified in energy; so that an immeasurable incident photon could be raised to five or more orders of magnitude.

As investigators found that the addition of special elements and gas mixtures produced curiously "photoselective" detectors, a strange breed of photosensitive tubes were developed throughout the early part of the Twentieth Century. These specialized photodetectors, "artificial retinas" as they were called, were used to select and discriminate colorations with extreme accuracy. A new breed of monochromatic sensors were implemented to detect infrared (caesium), red (cadmium, iron-selenium, sodium), yellow-green (barium), green (cuprous oxide), blue (rubidium), violet (lithium, potassium), ultraviolet (cadmium, sodium, strontium, uranium, zinc). Certain cell-types (cuprous oxide) responded to several colors, producing reversing photocurrent polarities for each color.

Such highly selective photodetectors opened a new potential in the art of point-to-point phototelephony:

the concept of selective and innumerable "color channels". Projecting pulse-code or vocal modulations, these "color beam" systems used special monochromatic gas-discharge tubes in conjunction with their peak photoselective tubes. The use of such specific monochromatic channels granted a rare secrecy to priority messages. The range of this special monochromatic communications technology was especially extended into the invisible spectra, where specific and numerous infrared and ultraviolet channels could be accessed where absolute secrecy was demanded. It was in the development of this monochromatic selectivity that bifurcation occurred in the art. Wishing to refine and expand this new communications trend, some pursued the development of more intensely monochromatic sources (MASERS), while others pursued the development of higher and more undetectable radiation spectra.

The development of spectral frontiers sought access in the hard ultraviolet and X-Ray regions. Without sensitive radiation demodulating detectors however, transmitted X-Ray signals were unnecessarily strong and dangerous. Seeking utility in this region, certain designers began investigating the use of specialized phototubes as high efficiency, auto-amplifying detectors. Radioactive sources were pulsed with quick acting plate lead shutters, as particle or photonic pulses were directed out through small pinhole collimators. These pulsating radiations streamed across the intervening space, producing identical pulsations in the receptive photodetector. Transmitted signals of this form used both particulate or photonic radiation as the carrier energy, a rudimentary pulse-code communications system. With weak sources, fluoroscopes were used to detect near zone radiations. A later example of this experimental trend appears in the "Ray Aviation Compass" of S. L. Weber.

The attractive feature of radiation carriers was their highly projective and penetrative nature. Material obstructions did not pose a problem when using these permeating beams. The early Lenard Ray and X-Ray signalling devices were, by comparison to the aethero-projective systems of Tesla, far more hazardous to personnel and far less efficient. The early development of telegraphic pulse-code demodulators was relatively easy, a means which tolerated the presence of modulator "noise". One could discern the received pulses as an audio "noise", the chaotic effect in metal target plates of the penetrating gamma radiation carrier. Radiation receivers were simple vacuum phototubes. Low pressure phototubes produced intensified noise signals, the result of harmonic enrichment in the inert gas atmosphere.

The effective range of these pulse-code systems could be greatly extended, neither by modifying the transmitter componentry or by intensifying the source output, but through a more highly selective detection method. All phototubes are radiation detectors. Though having maximum response in specific spectra, each photosensitive element or compound is possessed of innate responses among the ultraviolet, hard ultraviolet, X-Ray, and Gamma Ray spectra. Phototubes are therefore capable of sensing the most penetrating rays which any X or Gamma Ray source can propel. The development of a selective response detector, one having special selectivity in the energetic X or Gamma Ray spectra, would allow complete demodulation at the reception site. One tube design which qualified in these regards was the Geiger Ionization Tube.

3.5 RADIATION CARRIER DEMODULATORS

A design perfected by Hans Geiger in 1908 as a radiation counter, the Geiger Ionization Tube found experimental utility in X-Ray carrier communications systems. Itself being a very specialized phototube, the design was amicably suited for this purpose, its thin mica window representing a highly directional photodetector capable of responding to highly penetrative X and Gamma photons. Having wonderful dynamic characteristics as a detector of pulse-modulated beamrays, the Geiger detector tube was used as both receiver and demodulator of intentionally pulsed radiations. Geiger point-counters are excellent analog demodulators for pulsed code, having a rapid response-recovery time. They can produce remark-

ably clarified responses to incident radiation pulses.

The original Geiger design was later improved by W. Muller (1924). The original Geiger Tube used a thin aluminum axial wire to detect alpha and beta rays. Used with a thin beta-emissive window, the tube responded to low energy gamma rays. In another form, thin beta-emissive metal axial wire was used to detect more energetic gamma rays. In effect, the Geiger-Muller Tube is a reverse Lenard Tube. Used as a simple line-of-sight detector, the Geiger-Muller Tube showed ability to "read" and "decode" pulsed radiation signals. Despite these first experimental findings, the Geiger-Muller tube did not permit the high selectivity demanded by military requirements. Such primitive radiation detectors do not insure selectivity, and cannot therefore be relied on to ensure the absolute secrecy which military signallers demand.

The improvement of radiation signalling systems lacked two basic components: a truly monochromatic and coherent ray source, and a highly selective Geiger-Muller detector. Radiation signal beams had to be monochromatic and absolutely rectilinear in propagation between source and target. By making the radiation carrier output more nearly monochromatic, one could literally signal to the horizon with absolute secrecy. X and Gamma Ray modulators, which either rapidly "shutter" or vibrate radioisotopes within shielded projectors, are broadband quantum sources. Being mechanical systems which impress their modulations "after the fact", these systems lack the absolute monochromatic character needed to effect selective communications. In addition, they do not provide the highly collimated streams required for longrange secrecy in the signalling process.

Another problem especially emerged with the use of shuttered radioisotopes. The use of natural sources produced a broadband radiation carrier, one which often contained energies below X-Rays. Point-to point integrity was lost where skewed Grenz and Ultraviolet rays of a wide variety surround the central signal beam. These skewed rays have such high energy content that they may easily be read by any enemy photodetector. Proximity is not required when the initial beam is intense. Therefore a coherent X or Gamma Ray projector, capable of being easily and graphically modulated, became the primary component of necessity in the new art. The design of a highly selective radiation detector would complete the system as second component of necessity. Together each would permit absolute secrecy in longrange point-to-point signals.

Improved radiation detectors of the period effectively converted, clarified, and intensified their received X and Gamma carrier signals. These detectors became complex aggregates, internally employing multiple functions to achieve their efficient operations. A series of spark ionizing chambers were produced between 1920 and 1940, highly charged multiple plate arrangements in very low pressure gas atmospheres. Single incident rays triggered electrostatic discharges across the thin gas-capacitor plates, each individual ray trail thus being made visible. As detectors of radiation pulses, these multiple plate low pressure chambers could themselves admirably respond to individual rays.

Not having been designed for use as signal demodulators, neither Geiger-Muller ionization tubes nor spark chambers could provide the strong and distortion-free output currents which communications systems demanded. On the contrary, such tubes gave exceedingly weak and noisy responses in such applications. In addition, the energetic transformations occurring within the chambers produced a very slow response time. Though point-accurate per strike, spark ionization chambers were far too slow to be used in communications systems. Lagging response time was problematic in the communications application of early phototubes, the time-lag characteristics defining the difference between detectors and true demodulators. Such lagging responses were observed and measured in photodetectors, a remarkable evidence of various resonant responses in matter (Campbell and Stoodley, Metcalf, Tedham, Wheatcroft).

High pressure radiation detectors are very specialized autoamplifying phototubes. They are component aggregates comprised of highly articulate members, and comprising composite functions. Employing various radioactive members, the high pressure gamma demodulator effected a staged transduction of incident energy. Through impact with special radioactive targets, the received gamma radiation carrier pro-

duces bremsstrahlung. Cascading action brings the individual gamma rays down into the lower energy, higher mass-density of thermal electron currents. This densification is achieved through the use of several radioactive impact targets, and the high pressure inert gas atmosphere, closely spaced stages which slows and amplifies the cascading electron population. These high pressure detectors demonstrated an unexpected means for greatly amplifying radiation code signals, the traditional concept of ion mobility encompassing only hard vacuums.

The high pressure atmosphere represents yet another discovery, an alternative means for receiving and transforming gamma radiation carriers into densified signal currents. Thus, several concomitant electron multiplication effects are employed to convert incident gamma ray signals into readable electrical impulses. The high pressure target tubes were capable of producing superior demodulation of gamma ray signals. In their varied geometries and compositions, we yet discover a lost encyclopedia of previously undisclosed nuclear phenomena. The use of high pressure inert gas atmospheres had been found to greatly magnified incident X and Gamma Ray energy with particular speed; an unexpected discovery. Successful attempts at duplicating the characteristics of the high vacuum Multipactor, in high pressure inert gas arrangements, are found in the "Communications System" of DeLoraine and Goldstein (1951). This design represents a true vocal communicator for gamma ray carrier bands.

Immersed in high pressure argon atmospheres, multiple radioisotopic plates defied the previously discovered rules of low pressure photosensor design. Certain high pressure tubes use pinhole apertures to provide the incident radiation carrier with a greater mean free path between the internal target plates. Made of beta-emitting radioisotopes, these plates are designed to produce autoamplified cascades. Highly directional gamma detectors combine bombardment avalanche in radioisotopes with special shielding foils to produce intense collimations (Zigler and Elsen, patents). "Aperture amplifiers" are specialized capacitors, variations which produce enormous charge cascades with each insignificant admission of incident X or Gamma radiation carriers. The admission of very weak pulsed radiation code through the single tiny apertures, rapidly produced strong electrical signals (DeLoraine and Goldstein, Lord, patents).

3.6 THE MOSSBAUER EFFECT

The appearance of certain fixed design forms in LASER technology became laboratory standards. Unexpected discovery provided experimenters with a completely new phenomenon, one whose exploitation completely changed the face and direction of LASER research forever. The critical development, of which we will now speak, concerns recently declassified patents. It is in these patents that we discover rare and fundamental phenomena which enable a new Radiation Communications Technology.

Once a radiant energy has been secured, its attributes studied and understood, it may find utility in either a weapons or communications system. Inventors require the exploitation of some phenomenon in connection with the radiant energy which they have chosen, and phenomena require empirical familiarity with the behavior of materials and energies. It has too often been assumed that natural radioactivity is a phenomenon beyond human control, an irresistible auto-destruction of heavy atoms whose constancy of decay is as clocklike as the day. But there are obviously instances in which the radioactive decay of certain materials may be actually modified by external applications of energy. Forcing a radioactive nuclide to release its total fund of radioactivity in a short burst is obviously not as difficult as one has been led to believe.

Reciprocal photoamplification effects in highly ionized gases had long been observed. Using analogies with harmonic waveradio resonance, first researchers in the phenomenon imagined that the principle of "lumped resonance" might hold true at both molecular and atomic levels. Electrons were viewed as small resonant circuits, having natural resonant frequency in various bands of the visible light spectrum. If it were

possible to stimulate resonance in sympathetic wire circuits, why would the principle not hold true for atomic-sized circuits? Brilliant monochromatic beams from a sodium vapor lamp were directed into a sodium vapor sample by appropriate optical means. The incident monochromatic radiation from the activated sodium gas stimulated the inactive sample to a brilliant resonance. When two samples were stimulated to brilliance, and one directed through the other, a beam of very greatly intensified light was obtained. This unique atomic or molecular "resonance" greatly attracted the curiosity of a few enlightened researchers, forming the very early foundations of both MASER Technology.

A great many researchers marvelled over these "molecular" and "atomic" resonance effects, particularly typified in MASER arts, others considered the strong possibility that resonant effects might occur entirely within solid lattices. This concept led to the development of the first crystalline Ruby LASER. Additionally, a few perceptive researchers realized that identical resonance processes should occur for every quantum band. This theoretical consideration suggested that resonance effects might be found in the Hard Ultraviolet, X-Ray, and Gamma Ray spectra, a developmental line which successfully produced coherent emitters for each energy band. But the search to discover both X and Gamma Ray resonance effects brought forth a truly remarkable finding long before the development of recently declassified extreme quantum LASERS, one which was to completely modify the nature of communications arts forever.

Though not discussed in any academic journals as yet, the Gamma Ray resonance effect forms the heart of the new Radiation Communications Art in which Gamma Rays are the dense and facile carriers of articulate modulations. While yet a graduate student, Dr. Rudolf Mossbauer (1959) discovered that specific radioactive elements could be stimulated into gamma ray resonance. Mossbauer directed an external supply of monochromatic gamma rays into various radioactive isotopes, finding that they produced identical monochromatic outputs. This gamma resonant effect taught that certain radioactive isotopes could be stimulated to release more gamma rays than the amount delivered to them. Mossbauer found that he could stimulate his isotopes into a supersaturated state by continually supplying them with the requisite quanta. Brought to a state of supersaturation, Mossbauer observed the sudden release of gamma ray bursts several orders in magnitude greater than the input. Furthermore, when properly directed, the gamma burst came as a single coherent emission. Mossbauer had found the means for creating a true gamma ray LASER.

After Rudolf Mossbauer discovered the primary aspects of his strange effect, others began discovering its ancillary phenomena. Mossbauer used gamma ray stimuli from discrete sources to effect the resonant release of gamma bursts in special Lanthanides and Actinides. Theoreticians described the phase characteristics of gamma photons resulting from Mossbauer stimulations (Shapiro). Some experimenters discovered that the mere proximity of gamma absorbent matter near a gamma isotope source effectively modified the source, an anomaly. The coherent gamma emissions of Mossbauer resonant stimulations were strangely linked to their absorbers, a relationship modified by motion alone.

Special radioisotopes were rotated on special high speed rotors, demonstrating a phase modulation effect (Ruderfer, Ruby, Bolef). Slotted shields were made to rotate at high speed between isotope sources and absorbers, adding evidence that phase shifts were indeed occurring. Other variations of this experimental arrangement employed a moving wedge of absorbent matter. Made to rotate near a isotopic gamma source, both positive and negative phase shifts were observed (Novick). All of these researchers observed Gamma Doppler Shifts (Grodzins, Phillips). These findings strongly suggested the possibility of directly modulating Gamma Ray streams by movement alone. Previous attempts at generating and modulating Gamma Rays required Lenard Target Tubes arranged with special radioisotopic windows. But such systems did not generate monochromatic, coherent streams. The Mossbauer Effect did.

While the separation of isotopes and their absorbers revealed anomalous reciprocal effects of gamma emission and modulation, the mere application of stress on the isotope samples was found to produce successions of powerful gamma ray bursts. Here was an unexpected "piezonuclear" corollary to the

Mossbauer Effect. Isotope samples were applied to loudspeaker cones, and physically vibrated in the presence of absorbent materials. These vibratory analogues of the shutter-wheel experiments provided more accurate determinations of gamma burst states. Indeed, certain experimenters discovered a strange effect of vibration upon the isotopes themselves. With applications of increasingly high pitch, the loudspeaker-fixed isotopes produced continual bursts of coherent gamma ray energy. Here was evidence that the mere compression of specific isotopic material could produce an intense gamma supersaturation. What had been observed constituted an avalanche process, one capable of organizing coherent gamma emissions.

The application of audio signals (400 cps) caused remarkably intense gamma emission in these isotopes. It was soon found that ultrasonic vibrations produced staggering gamma emissions. The ultrasonic magnification of gamma bursts was the obvious result of internal strain. As ultrasonic compressional waves ride through special isotopes, Mossbauer Isotopes, they produce a remarkably potent state of supersaturation. A growing wave of gamma photons is thus both stimulated and driven along by compressional waves alone.

This supersaturated condition is entirely dependent on the pitch and volume of tonal power delivered to the isotopes. Intensely coherent gamma emissions emerge from both sample ends, beamrays of lethal potential.

Those devoted to weapons research had realized the import of a controlled gamma ray reaction. Large level gamma bursts were produced by these compression methods. Continual compressions produced continual gamma bursts, the piezonuclear effect occurring with tremendous efficiency. Researchers who studied the compression phenomenon may not have been prepared for the resultant gamma yield when shock impact was applied to the isotopes. Huge coherent gamma ray bursts were produced throughout the small isotope core, a radiance which may have produced the first uncontrolled gamma ray "event": an explosion of pure and penetrating gamma superradiance. The development of gamma burst "explosives" has well remained completely shrouded in secrecy. In the course of developing this program, most likely at the cost of several lives, a means for controlling the process was thereafter approached with the greatest care. Small samples of the "Mossbauer Isotopes" were permeated with tiny increments of ultrasonic energy, the resultant gamma yield bearing the highly modulated signature of the audio tone. The more intriguing chapter in this developmental line however has more to do with the communications theme.

3.7 JOSEF EERKENS

The initial experiments with radioisotopes and moving absorbers were surpassed by new variations. Some researchers tested crystal LASER analogues of the Mossbauer Effect, employing crystal substrates which had been doped with a succession of different gamma isotopes. Each crystal matrix was examined in order to discover some new gamma resonant transitions (de Coster, Pollak, Amelinck). New gamma peaks and resonant states were discovered in electrically conductive crystals (Wertheim, Norem, Ludwig, Woodbury). These experiments proved it possible to use combinations of radioactive dopants in order to stimulate and elicit very specific gamma radiant states. Experiments with amorphous substrates determined the importance of crystalline structures in order to facilitate the stimulation of Mossbauer emissions (Pollak, de Coster, Amelinck).

The most valuable patents in this collection, if only for the elevating information which it brings, may well be those granted to Josef Eerkens. Eerkens (1962) discovered that the application of strong axial magnetic fields to rodshaped samples (of specific Lanthanides) could produce a more highly coherent organization of gamma ray emissions. A "superradiant" beam was found to emerge from both ends of such rods. The discovery that gamma ray emissions could be cohered in preferred directions was yet super-

seded by methods which actually effected the direction of gamma bursts through a single rod end. Eerkens found it possible to cause the coherent gamma burst to emerge from a designated rod end, by pulsing the rod with gigacycle ultrasound. Producing travelling compression waves in the isotope rod, it was found possible to actually direct the mounting gamma cascade from end to end. The powerful coherent gamma blast was thus capable of being directed, a previously unheard potential.

In the Eerkens design we see a true Gamma Ray LASER, or GRASER. The unit provides both intense and directional beamrays and an extremely facile communications potential. It represents, I believe, the most advanced system in this declassified collection. Both the device and its description are intriguing to science scholars because it reveals the very existence of natural phenomena never before suspected. Privatized and horded for military reasons, the Mossbauer Effect represents a step which places Radiation Communications Technology far above all others. Eerkens found that the same radioactive materials could be forced to discharge their radioactivity in sudden voluminous bursts when properly stimulated. This latter effect violated the concept that radioactive half-life is an immutable constant, for it was found possible to control the decay rate by a special "enhancement process" involving acoustic energy.

Eerkens found it possible to actually control and determine the decay rate of the radioisotope by forcing gamma emissions through the application of ultrasound vibrations. Frequencies necessary for the control of radioactivity is given as lying between 1 and 10,000 Gigacycles. He states that the increase in these ultrasonic frequencies eliminates the need for axial magnetic fields. In a variety of energetic stimulations, Eerkens found that microwave energies produced all the combined effects of both magnetic orienting fields and ultrasound applications. These Mossbauer Gamma Ray LASERS produce "superradiant beams" whose suggested applications include "radiation weaponry, in the melting and evaporation of materials for the purpose of welding, cutting, and machining...".

Unexpected and anomalous from every theoretical standpoint, The Mossbauer Effect represents a phenomenon by which every tenet of nuclear physics has been overthrown. The "Gamma Ray Laser" of Piekenbrock (1971) is another patent which extended these principles. Having utility in both weapons and communications applications, this system uses Mossbauer isotopes in yet another activation mode. Direct bombardment of the isotope plate with high energy electrons reveals a means more powerful than the microwave method of Eerkens. This patent features the use of a gamma "optical" resonator cavity. Highly polished crystals of pure germanium or silicon crystals are arranged in quadrature, the optical cavity sustaining and intensifying stimulated gamma states through successive Bragg angle reflections. The author corroborates the discovery that radioactive decay rates can be controlled, made to yield its entire energetic fund in a short increment of time. In this capacity, the device represents a weapon of frightening potential.

Operated in burst mode, the optically regenerative system of Piekenbrock can produce a succession of 30 Gigawatt blasts. One cannot imagine such penetrating gamma superradiance. In this use, the inventor cites its utility in "...the interception and destruction of missiles, tunneling through mountains, well drilling, and for road and canal building projects...". In continuous operation, this system also constitutes a true modulator of gamma beamrays. While the weapons potential of these devices is clearly stated in the patent documentation, the use of the designs as gamma ray modulators may not be so clear. These systems can be easily modulated by simple means, producing any desired coherent Gamma Ray intensities. Indeed, the Eerkens Patent teaches that "when modulated, the gamma beam is useful for communications". Thus once again, military personnel grasped the implications of Teslian radiant methods all too late. Their attempts to achieve some fraction of his more life-elevating methods actively pursued the use of X and Gamma Beamrays specifically for point-to-point communications.

One does not survey these astounding developments without some surprise. Patent study reveals a curious and wide divergence between Mossbauer Technology and the confusing sequence of inferior mechanical modulators which kept appearing at later dates. Several variations of the mechanical modula-

tors were repeatedly patented throughout the later Cold War years (Black, Fanning, Wanetick, patents). Study of both mechanical and electronic bombardment gamma modulators reveals the remarkable phenomenon of design repetition, a recapitulation which lasts beyond the admitted date of the more revolutionary Mossbauer Technology. The continual appearance of these inferior mechanical designs demonstrates the degree to which information had been withdrawn from the scientific community, it having been quite obvious that the Mossbauer Effect and all of its corollaries were absolutely classified until very recently. This is why it is possible to find endless repetitions of the same mechanical Gamma Ray modulators, where only Mossbauer Technology should have dominated the scene.

3.8 RESONANT GAMMA DEMODULATORS

While the detection of pulsed-code radiation could employ inefficient Geiger-Muller tubes, the demodulation of vocal signals required far more graphic and fidelity-restrictive audio outputs. The improvement of radiation carrier technology required several advancements. First, a means for producing greatly enhanced graphic modulations of signals, including vocal signals, defined the pursuits of one research group. Others developed means by which carrier intensification and beam collimation could be obtained. The most important study avenue however was that which developed highly efficient radiation carrier receivers.

The first radiation carrier systems best operated in pulsed mode because of both their inefficient transmission qualities, and their poor response in carrier reception. Properly understanding the nature of transmitters and receivers gives us deeper insight into the problem. The improvement of any communications system begins with improvements in reception characteristics. This is no different for a radiation carrier system. It is the reception process which truly defines the limits of a communications system, not the transmission process. While with waveradio, the inability of amplifying received signals demanded multi-megawatt spark transmitters, a gradual progression of designs taught that efficient detection and amplification permitted much smaller transmitter stations. An efficient receiver lessens the required transmission intensity. It is the same with all communication systems, regardless of carrier species. Any highly efficient receiver greatly diminishes the necessary power of a transmitter. Radiation carriers need not be so dangerously intense when the receivers are very highly efficient.

By comparison with Lenard and X-Ray signallers, much improved Gamma Ray Communications Systems have more stringent and restrictive requirements, emphasizing the need for much improved "cooperative" transducers. The employment of modulated radiation carriers demands very specialized resonant receivers. Existing Geiger-Muller tubes could not provide this fidelity, a property of their both their material compositions and geometric symmetry. Gamma Ray carrier systems require gamma-resonant receivers. But how do radiation carrier receivers differ so appreciably from other communications receivers?

Simple selenium and caesium tubes had been early implemented as radiation carrier receivers because they represented the most direct means for producing an electrical signal from an incident radiation carrier. But the process was not efficient, much energy being chaotically reflected away during absorption. None of the commercially available Geiger-Muller Tubes were designed to best utilize the incoming gamma ray energy. These produced their noisy response to code fluctuating gamma beams because they lost most of the signal on reception. Photodetectors are target structures. They are made to respond when struck with various species of radiation. This is especially true for the photosensors known as ionization chambers. In each case, incident radiation of certain wavelength results in a photoelectric process. When incident radiation cooperates however with the target structure, the incoming energy releases an anomalous density of photoelectrons. Signals of a remarkable intensity may thus be obtained from seemingly insignificant incident rays.

The progressive development of specialized photosensitive tubes, and their conversion from detectors to demodulators of radiation carriers is a rich, fascinating, and informative bibliography. The numerous varieties of Geiger-Muller Tubes, scintillation counters (Lundberg, Youmans, patents), sulfur crystals (Parsegian, patent), halogen crystals (Taylor, patent), and semiconductor wafers of various geometries (Horton, Calaway, patents) provided invaluable data on elemental target response to gamma carriers. Some of the early photodetectors provided anomalous high efficiencies when used with specific gamma ray spectra, the result of strange quantum-lattice interactions. When it was found that efficient X and Gamma Ray carrier demodulation required a resonant absorption of the incident carriers, a great variety of existing vacuum and solidstate devices were studied and modified.

The production of superior resonant receivers in the gamma carrier band was thus realized to be predicated on certain highly anomalous dynamics. These dynamics have yet to be explained by conventional physics. The impact of X and Gamma radiation so loosens the crystalline lattice of photosensors that they become, for a brief moment, fluidic at point of incidence. It is in this brief instant that anomalous energetic transformations can take place within a lattice structure. In certain radioisotopes, gamma rays are emitted when atoms shed excess energy. They do so without otherwise transmuting their nuclei. Contrariwise, the absorption of a single incident gamma photon, in a crystalline lattice of the appropriate element, can result in an enormous release of energy. It is for this reason then, that certain elemental phototubes are very potent detectors and unexpected amplifiers of incident radiation.

Nikola Tesla and Gustav Le Bon both independently discussed and demonstrated these principles in several experiments. Tesla was able to effect sub-electron transitions by the violence of special arc discharges. Le Bon provided transitions equal to those emanating from Radium by he use of focussed sunlight and "resonant" metal lattices. Dr. Le Bon proposed the existence of an energetic particulate medium between and among atoms, an "intra-atomic" energy. Dr. Tesla referred to this continuum as the "ambient medium", a clarified name for the Aether Gas. This topic area, one largely abandoned after the Victorian Epoch, led several researchers into deeper study of nucleonic processes. Experimenters considered that special particle bombardments could breach nuclear barriers, releasing subatomic particles in the process.

The notion of securing new kinds of energetic current began making more sense. By this reasoning, we may understand what Dr. Tesla achieved. His accidental discovery of "white currents" may have been a fortuitous intra-atomic resonant effect, one in which streams of aether gas were liberated from between and among the atoms of his discharging components. The violent impulse currents were simply used to effect this release. The special nitrogen arc discharger which Dr. Tesla later empirically designed, may have managed the amplification of this effect.

Comparing the different aether currents of Tesla and Le Bon against conventional terms, physicists equated the streams with electrons or neutrinos. Completely misinterpreting the Victorian reports, some began studying gamma ray excitations. While this study area opened a great many new discoveries, it never managed to unlock the mystifying lock yet closed on the aetheric treasurehouse. Those who sought these secrets were not prepared to implement the methods of Tesla or of Le Bon in securing real aether currents. Misconceptions, misinterpretations, and misrepresentations flood the pertinent bibliography. The several steps, through which conventional physicists abandoned aetheric theory, resulted in a hardened attitude toward the more "measurable" atomic and subatomic particle species. Nevertheless, the anomalous discoveries continued to make their appearance, especially when excess energies emerge from high current electrodischarge tubes (Paneth). No conventional model could satisfied the requisite conditions for the mysterious observed efflux of heat and white light, an astounding efflux which continued long after the stimulating discharges had been withdrawn.

Bombardment studies on matter commenced with the ion tubes of von Laue, tubes by which remarkable supermagnifications of individual tungsten crystal atoms were obtained (1906). Frenetic and headstrong, a successful academic purge very methodically replaced every theory, phenomenon, model, and

embodiment which represented the Aether. Each aetheric attribute was equated with measurable "known" identities. With the discoveries of J. J. Thomson, aether gas was first renamed "electron gas". With the abstractions of Einstein, aether was renamed "space". With the theoretical research of De Broglie, aether was termed "particle pair saturated space". Later discovery repudiated all these, referring to "neutrino gas". Modern theorists have resorted to a "seething quantum gas" in place of the aether. Each of these repudiations and rephrased attempts have only emphasized the absolute need to recognize the fact that space is flooded with an interstellar medium, the Aether.

The dynamic interchange, by which incident radiations and matter are actually interconverted, may not require the excessive conversions claimed by so many contemporaries. Lacking knowledge of the peculiar resonances germane to such Late Victorian anomalies provokes the designers of nuclear systems. Those whose fund of knowledge is limited to the conventional dialogue, theoretical structure, and other permitted expressions, have missed the best of opportunities. Accident, serendipity, prepared observation...these represent fortuitous "shortcircuits" in the progressive development of science and technology, and should be embraced rather than derided. Experimenters, the fortunate recipients of all too numerous such "accidents", obtained greatly elevated knowledge when anomalous energies made themselves known. Tesla was one individual whose accidental discovery provided a simple means for obtaining a stream of energetic aether gas, whose technology was well proven by nearly a half-century of equally anomalous demonstrations.

The Multipactors and Photomultipliers of Dr. Farnsworth combined both materials and geometries in order to amplify the smallest scintilla of incoming light energy. External energy supplied to the tubes amplified the output of these complex tubes to five orders of magnitude. Because of unusual bombardment-resonance effects, the alkali metals were found especially sensitive to the extreme spectra. Evidencing anomalous response in these extreme spectra, metals such as potassium and caesium release uncharacteristic volumes of electrons. Defined by Dr. Le Bon (1906), specific incident wavelengths in specific target elements most powerfully produce photoelectric outputs.

Thoriated alkali elements produced uncommon resonant spectra when electrically bombarded. The resulting photoelectrons were increased up to 200,000 times after exposure to insignificant amounts of visible light. It was also found that radioisotopes became stimulated to unusual photoelectric levels when energized by sharp electric discharges. This discovery was repetitiously learned when a variety of radioactive detector tubes were developed just after World War I (Ainsworth, Winkelmann, McElrath, see parent text). Continuously appearing throughout the Patent Archive years, these radioactive receiver tubes left their permanent legacy. Their bibliography is a anecdotal record replete with anomalous energy amplification effects. In each case, the high efficiencies were based on the fact that incident radiations were completely absorbed.

A study which began with the crystallographic research of von Laue, and which culminated with the stimulated emissions science of Townes, quantum theory provided certain successful models toward these ends. One would not expect such highly efficient output currents without the highly specialized "quantum design" of absorptive targets, by which researchers found themselves able to obtain enormous particle yields with insignificant input energy. Thus, by simply taking the time to properly arrange both absorptive materials and incident wavelengths, experimenters could obtain unheard and unexpected transformative maxima. Such apparatus employ the resonance-bombardment effect to obtain significant and clarified outputs, those necessary for vocal communications along a gamma ray beam (DeLoraine and Goldstein, patent).

The various quantum phenomena which were embodied in these tube designs, exploited these resonant absorption effects to produce highly efficient "gamma resonant" conversions. Resonant radiation demodulators receive incident gamma carriers and resonantly liberate free electric charges with highest efficiency for a particular gamma wavelength. Resonant demodulators are specialized absorptive target tubes, detec-

tors which constructively resonate with the gamma ray spectra for which they are designed to respond. Yet, the perfected art did not become available until the remarkable Mossbauer Effect again revealed an astounding corollary.

The Mossbauer gamma resonance effect provided an exploitable resonance phenomenon, one by which the most advanced demodulators of gamma ray carriers have been devised. These designs provide the highest fidelity vocal communications along gamma carrier beams. Resonant radiation demodulators convert incident radiation into electrical currents with virtually no reflective losses (Schiffer et al., patent). These phenomena were dimly foreseen by W. C. Peckham (1896), who believed that X-Rays were resonantly emitted and absorbed. According to his view, improper material resonances would not emit X-Rays. This model was indeed proven, when it was found that certain target elements would not yield the same amount of X-Radiation as others. Gamma resonant demodulators are necessarily coupled to their transmitters, but do not so much require signal intensity as they do signal wavelength. The Mossbauer Effect opened the principle of "channel selectivity" to Gamma Ray Technology, channels never before realized in LASER science (Reiffel, patent). The gamma tuning process is one by which system operators may literally delineate specific Angstrom channels, even as waveradio operators rate their transmission channels in "frequencies". Because of these resonant modes, there exist preferential Gamma Ray "channels".

Because of the highly classified nature of this technology, most radiation detector patents rarely declare their true purpose (Deming, Weber, McDermott, Calaway, Chope, Tomiyasu, Jernigan, patents). Most are portrayed as "prospecting systems" (Herzog, Lord, Youmans, patents), "testing instruments" (Fua, patent), and "measuring systems" (Reiffel, patent). Several do not declare their true purpose at all, ignoring the issue altogether, and preferring to briefly state their operation characteristics (Horton, Desvignes and Hunziger, patents). The very obvious application of communications-relevant components in the Radiation Arts is made all the more evident by the several complete systems openly declared and declassified.

3.9 GAMMA IMAGING SYSTEMS

Gamma ray television systems are based upon fundamental principles established toward these ends by Nikola Tesla in 1893. Nearly two years before Roentgen made his announcements, Tesla had been observing shadowgraphic effects from his various high vacuum globes. In certain instances, he had observed the fluorescent effects of these globes against special chemiluminescent screens, usually of platinocyanide. Tesla observed shadows produced when the outward expanding flow of "Very Special Radiation", an aetheric streaming, was obstructed by his own body. Here then was the first televisual projector, a precursor of military gamma ray video. The projection method of Dr. Tesla, later described just prior to World War I, suggested infinite televisual possibilities to other researchers of his time. His system was constructed in two basic components: the image projector and the image reader. Images intended for transmission were placed in a large area column of "very special radiation". The system thus described by Tesla utilized his special aetheric beams.

Images chosen for this purpose were geometric masks made of some electropositive metal, usually of zinc. These obstructive masks were placed directly in front of the emerging column. Thus impressing themselves onto the invisible aetheric beam, their form was projected out through space. This "whole image" projection technique was exactly analogous to the magick lantern projectors of his day, with the exception that the rays were both highly rectilinear and penetrating. The projected images were intercepted at any given distance with a fluorescent screen, the resolving component. Images projected in this manner were always "in focus" so long as the fluorescent screen was held perpendicular to the ray column. Brilliantly illuminated by the impinging energy, the screen was an effective target which revealed the

transmitted image without distortion. These images demonstrably retained their integrity across any given distance. Tesla showed the projection of simple shaped patterns across several hundred feet, a demonstration intended to prove the feasibility of projection across several miles.

Tesla television is simply a magick lantern. The main difference between the two is that aetheric projections effortlessly pass through most obstacles. Whole image projection is geometric image projection, a shaped beam television method. The beam carrier is impressed with the image, transmitting whole images as a fixed geometric distribution. The essential beauty of this televisual form is the complete absence or need for excessively supportive and highly synchronous scanning systems. Typically, a great many others misinterpreted the Teslian whole image projector, insisting that he employed intense X-Rays as the fundamental image carrier. Later researchers insisted that the carrier rays were a soft gamma emission. Tesla transmitted legible writing with his method, a matter of bibliographic record. presented some minor difficulties. These were solved by the use of thin glass screens and lead letters, the geometric whole-image transmission being the essential "picture of simplicity".

Some scientific researchers easily adapted their misconceptions of these popular disclosures of Dr. Tesla. Those who considered the Teslian rays to be mere X-Radiation devised bold and dangerous projection systems, testing their primitive X-Ray image lanterns with special darkroom fluoroscopes. X-Ray imaging required opaque projection techniques, and dangerously penetrating rays. Various apparatus secured X-Ray columns through the use of large surface area targets. These large area X-Ray columns were then appropriately shaped through opaque masking. The emerging beam, a rectangular column of several square inches "window area" passes through a prepared image. Images were made from lead foil and placed on thin glass or mica sheets. Thomas Edison and a great many experimenters remained fascinated with the scintillating images produced across rooms by their powerful X-Ray and Lenard Ray lanterns.

The notion of frame-teletype projection was handled by Dr. Tesla in the same direct shadowgraphic manner, prepared slides being placed before the beam projector. The impressions of the occlusions and transparencies were discerned across the transmission space by the use of his special high-brilliance fluoroscopic screens. Miniaturized, such teletype plates could be produced by the engraver's art, a window of two or three square inches. Projected out through a space and received in a small fluorescent screen, ordinary optical lenses could expand the otherwise small teletype image for reading or projective purposes. In articles which were written for the Electrical Engineer, Dr. Tesla revealed a great number of long distance projected shadowgraphs and typographs.

The Teslian ray projection of live images required more developments in the first simple stages of the art. With the energetic effluves which he used, there were no hazards in direct and continual exposure. The shadow images of persons who obstructed some portion of the beamray were directly impressed on the outflowing ray column. While these images were mere shadowgraphs of "live scenes", other adaptations would permit the application of vivid, well illuminated imagery to the energetic carrier. Tesla observed these moving images, paying special attention to the "granular density" of fluorescent materials applied to the screens. The reason why he pondered this problem was to better obtain more graphic resolution in the projected images.

One solution to this singularly intriguing technical impasse was the implementation of bright arc lamps and optical focussing systems. The light of brilliantly illuminated "live" scenes would be focussed onto mirrors. These would be so arranged to project their brilliant miniature scenes onto a special photosensitive beta-emissive target plate, the window of a large area Lenard Tube. A large, flat cathode plate discharges against this window, projecting a variable density X-Ray column, the result of bremsstrahllung. Depending upon the granular refinement of the target window, this variable density X-Ray column contains the exact geometric representation of the live optical scenes. Distortion in the reflected image, that which falls onto this Lenard window, is optically corrected by appropriate elliptical lenses. These X-Ray

projections are resolved at the reception site through any number of several fluorescent screens (Masi, patent), electrically amplified fluorescent screens (Kell, patent), large area scintillator windows (Lundberg, patent), and a great variety of newly declassified scanner-imaging systems (Takahashi, Schmidt, Cox, Pandelisev, Taboada, Riedner, Spivey, patents). These latter systems allow separation between the source gamma column and those viewing the screen.

3.10 COMMAND GAMMA RAY SYSTEMS

But X-Ray systems were not nearly as penetrating as gamma ray carriers, and the Mossbauer Technology made several remarkable appliances possible. Since gamma ray beams have both an extreme penetrability and rectilinearity, they are therefore capable of travelling through far longer distances than X-Ray columns. The new and sensitive Mossbauer receivers make possible a communications carrier which may be exceedingly weak in power. Being so weak a column of energy, such systems may operate in an intermittent manner without fear of being identified by foreign surveillance.

Gamma ray integrity...whether as a thin thread, a pencil, or a column...is not lost with distance. The nature of the exchange medium permitted wireless transfer of power without concern for distance, a strong connective link being established between Gamma emissive source and receptor. Gamma Ray communications carriers can move through walls, projecting its signals straight to any appropriate receiver. The technology was extended when once the development of coherent X and Gamma Ray LASERS had been secured. Since directed Gamma beamrays need be no wider than a "pencil", their streams may be treated as incident radiation. The demodulators therefore behave as targets, ideally absorbing the whole incoming stream without reflection losses.

Three variables can reduce the effective clarity of a Gamma signal: insufficient source modulation, beamray divergence, and distortion losses in the demodulator. Mossbauer Technology removed these lossy potentials, securing the technology and placing it far above all existing systems. Gamma Ray signals suffer from none of the meteorological variables whose distortive actions so distort waveradio signals. Gamma ray signals can pass through exceedingly thick layers of water and water vapor without any distortion. Their implementation permits a resolution which very greatly exceeds every other carrier species. Possessing the highest potential "graphic density" of all photon species, very high resolution whole images can be exchanged through a low intensity gamma ray column. Satellite Technology resolves the heads of civilians on the street. With Gamma Ray carriers of (0.01 to 0.001) Angstroms, one can "examine" individual hairs on the head of civilians on the street.

With most early X-Ray and gamma ray applications, a simple pulsed code transmission was easily projected through most obstructive materials (Weber, patent). The very minor distortions of passing through enclosures or hulls would not appreciably distort or greatly modify a gamma ray signal. The task of utilizing such beamrays for the transmission of video matter offered a far greater challenge. Gamma carrier television is not a hypothetical possibility. It is a reality. Thin Mossbauer isotope rods are packed together into a large matrix, a "window" which very easily becomes the projective source for live scenery. Each rod of such a matrix is the pixel of a projective column which is sent through space as a Gamma Ray carrier. A Mossbauer Matrix is stimulated by the back projection of whole images which have been intended for transmission. Scenery, which is impressed as focussed LASER light on one face of such a Mossbauer matrix, becomes a variable density gamma column. The column contains the representation of moving images, a projected carrier beam having highest graphic detail. Projected to its target receiving station, it is resolved through an identical Mossbauer Matrix. This receiving unit absorbs, amplifies, and converts the columnar carrier into a fluorescent display.

Radiation modulators project intensely penetrating emissions, a communications channel of unprec-

edented characteristics. When considering X and Gamma Rays, the effect of "broadcast distance" between transmitter and receptor becomes ambiguous. Extremely rectilinear and irresistible, X and Gamma Ray projectors can operate effectively through either a millimeter or several hundred kilometers of separation space without any seriously detectable difference. Since Gamma Rays cannot easily be stopped or distorted in passage through most natural material barriers, they become the carrier beam of choice. This is especially true when considering the kinds of communications links which Gamma Ray carriers could establish. Gamma ray communications represent a system which obtains unblocked, unjammed, and unaltered point-to-point contact among command centers. The instantaneous and failsafe communications network needed by various command centers has thus found its perfection in Gamma Ray Technology.

During the early years of the Cold War it was not uncommon for children to thrill to the sight and sound of delta-wing air power, aerial formations which streaked across the city sky with great regularity. All that is ended now. Airpower need never be deployed in patrol functions again unless so directed. When they appear, they appear with a determined mission as governed by those who watch and command. Satellite eyes monitor the globe with cliched and familiar, yet unbelieved resolutions. These watchers are never hampered by the night or by cloudcover. They merely select a specific retina, and continue watching with unbroken resolve. For gamma ray "light", virtually no intermediary occlusions exist.

The late Cold War years, those preceding SDI, proved that scientific armadas had indeed conquered space. But these armadas were robotic systems, a continual airlift of enormous espionage satellites. The consistent cover story proliferated the transparent tale of peaceful geophysical studies. The technologies of photodetectors and high resolution video surveillance, and space technology, whose conjunct development was stimulated during the years following the U-2 incident, have been fused into an implacable alliance. One not only can see everything on the terrestrial surface, but one can see it regardless of time or meteorological conditions. In fact, one can see deep into the terrestrial surface. Gamma Ray Technology has provided the means. A wide selection of available spectra have provided the watchers with far more than "geophysical" data. The "spaceoscopic" arsenal is a matter of declassified fact.

In the absence of hard data concerning Gamma Rays, there are those disclosures which, while representing encrypted surveillance systems, actually inform, corroborate, and empower our theme. We may thus derive adequate information from these disclosures to learn much more than academic texts ever tell. There are those patents which describe a great many Gamma Ray "prospecting methods". The "Mineral Detection Apparatus" of Duffey (1972 declassified) is far more than what has been claimed. Here is a radiation technology which employs neutron and gamma beam transmissions in scanning operations. One requires but a small leap of the imagination to realize that both the disclosed bathysphere and 2-man submersible represent deep space orbital stations, a surveillance system (misrepresented) being more or less completely disclosed.

Various disclosures teach much concerning the behavior and attributes of Gamma Ray differentials above the ground. High altitude surveillance teaches much concerning the feasibility of Gamma Ray inspection and communications links (Teichmann, Lord, Herzog, Youmans, patents). Gamma Detecting instrument packages, cameras and directional photosensors, now police the potential orbital munitions stores. The space residence of these instrumentalities are openly described on behalf of obvious "national security" and International Space Law. This necessary surveillance of nuclear material in space, a patrol of every foreign launching, has its other functions. Satellite footage of the earth surface has become the common feature foldout of popular magazines, Sunday rotogravure sections, and a host of Cable Television presentations. One thus surveys a wide range of optical and paraoptical views, a very detailed reconnaissance in a grand variety of spectra. The colorful tapestry revealed before the casual and uninitiated observer represents an unfathomable potential. Each such satellite survey evidences a vague shadow of the actual tactical military potentials, now secured.

Once the greatly desired advantage of military commands the world over, geosynchronous patrol sta-

tions sweep the earth with robotic regularity. The dubious and fascistic dream of Dr. Von Braun has been partly achieved where, cloaked in peaceful attire, the watchful eyes of endless unmanned squadrons patrol the entire globe at every instant. These are not watchers and holy ones however. They are military agencies whose functions are not entirely clear to civilians. The fact remains that military command now has committed itself wholly to its satellite technology. This absolute reliance on the existing enormous aerial network has become state of art. With the establishment of this satellite ring, there can be no other systems competitive technology. In both communications and weapons technology, there can be no equal. The entire global surface becomes an opened book, free for the prying eyes to do as they will. A dangerous potential for the ambitious.

Orbital weapons platforms, while not bearing nuclear fission or fusion packages, nevertheless each represent greater potential lethalities. Gamma Ray LASERS have been detailed in previous sections, the gamma ray "flash bombs" having been described to some degree in the parent text. Gamma Ray communications systems interlink strategic points on the globe with pinpoint accuracy. Poised in deep space orbits, these geosynchronous stations rest in undetectable positions. When so required, the use of multiple relay methods prevents any one "gamma" satellite from being observed. Densely compressed messages are continuously redirected among a host of these gamma relay posts in space, producing only a spurious and deranged gamma "flicker" when surveilled.

Command oversight of each potential theatre of action is secured between a vast regime of highly integrated earthlinks and the synergistic halo of military satellite stations. Gamma Technology is formidable, a vast assortment of remarkable apparatus. With the available Gamma Ray technology we may well consider the state of military communications Arts, against this Art perceiving somewhat of the existing waveradio systems and their fate as inferior technology. How would a Military Command employ these systems? One can prove the possible connective links in such a system, using those LASER models of the past technology (Tomiyasu, patent). Ships, aerial squadrons, submersible vessels, land forces...all are linked through the existing system of orbital stations. Gamma carriers form the links of an immense communications web. Tactical submarines, however deeply submerged, do not have to surface or utilize outdated periscopic techniques.

Satellite reconnaissance can provide submerged vessels with superhigh definition television images, the detailed closeups of course surroundings. Submarine crews can thus view the details of air, sea surface, and undersea conditions in a wide circumference surrounding their vessel. Submarine point-to-point communications are routine, Gamma carriers providing flawless interlinks in a great variety of possible combinations. These are systems communications links which cannot be broken. Why would there be any need for the former systems? Unwieldy, mammoth, susceptible, and costly, waveradio systems are obsolescent. We have indeed arrived at a place in history where the Oligarchic Power reveals itself plainly. With no threat of warfare, there is no reason for the surveillance operations. Furthermore, with such a complete system in its innumerable and inaccessible aeries, there are several questions which others must now answer.

The seeming contemporary ambiguity of "friend or foe" covers far too many desiderata concerning geopolitical themes. Why the continued monitoring? Who is directing, and who is receiving these reports? Are we simply learning more of the true oligarchic nature, whose methods and ambitious programs wait for no one? Leaning out in an endless drive toward continued and prolific masteries of greater social proportions, such oligarchic rulership believes it has achieved the ultimate in terrestrial management. But, terrestrial management...in whose name?

EPILOGUE

Students of the Patent Archive must search those records with a trained eye. However convoluted the historical records, one nevertheless piercingly perceives the true utility of any patent. Only an awareness of patent potentials can steer the path, familiarity with the historical bibliography being a primary requirement. The encryptive intrigues of otherwise high classified military patents is often presented to the student beneath a coverture of innocence. Weapons-potential systems are often misrepresented as "medical devices", a horrifying and cruel perversion of language which reveals the motives of those who design. Indeed, it has often been my horrifying experience to note the numerous publications which cite X-Ray LASERS as having been designed specifically for use in the "medical sciences". The lethal application of deadly LASER yields to human subjects is usually associated with those criminals who pursued such objectives in Nazi Germany. When Lawrence Livermore Laboratories, a weapons developer, declassifies an X-LASER patent (5.103.452) and claims it to be a device for "producing holograms", one becomes especially resolute and severe. The intrigue becomes grave when reading that the device is intended for "producing holographic images of biological specimens", understanding the infernal depths cloaked in that phrase. In one such instance, a weapon was described as a "microscope illuminator", another as a "full body tomography scanner", yet another as an "exploratory tool". While most such packages are content to present themselves as engineering exercises, the designers blinding themselves with erudite discussions on quantum transitions, their true purpose cannot be hidden.

X and Gamma Ray LASERS, specifically cited as having application in the manufacture of etched silicon technology, ameliorates the conscience of a few researchers who are willingly deceived. The military application of any such system is overwhelmingly obvious, especially when noting the true identity of each such patent assignor. "Optoexplosive Device" (De Ment, assignor to United States of America), "X-Ray Laser" (Wood, assignor to United States of America for the Atomic Energy Commission), "Excimer Laser" (assignee NRL), "Coherent X and Gamma Ray Emitter" (Viecelli, assignor to United States of America for the Atomic Energy Commission), "X-Ray LASER System" (London, assignor to United States of America for the Department of Energy), "X-Ray LASER" (Nilsen, assignor to United States of America for the Department of Energy), "Coherent X-Ray Production" (Cochran, assignor to The United States of America as represented by the Secretary of The Navy). Each of these weapons mentions utility in the "medical arts". Each cites utility in various high-tech "manufacturing processes".

Of the weapons inventors themselves, I have only the very lowest opinion. I am not enthralled with those who hide their malicious nature behind a false patriotism. It is not for any nationalistic cause that these persons labor. If the cause for which they are so devoted did not exceed national interests, then they would be guilty of treason. They have too boldly sold their nation out to the eyes of those who search for advantage, patent declarations tell the military soul of any nation. They also reveal the weaknesses of a national defense system. I have no doubt but that these declassified patents have already been superseded by a far more potent and revolutionary technology, one whose "working substance" is an exchange medium of extreme flexibility. We do not require these facts here. The present text has been published for matters of scholarly elucidation on natural phenomenology. Our single aim is philosophical in essence. The pursuit of world foundations, matters of consciousness and the structure of reality is our single theme.

Patent classification does not always require a complete withdrawal from the publicly accessed Archives. Otherwise highly classified patents do flood the Archive as carefully misrepresented disclosures. Deception through open visibility. The art of investigative patent research requires the discovery of a theme, the Archive contains the proof. One very discretely examines related patents, realizing that the greater majority of relevant and critical disclosures will never be found until released to the public. Most civilians will never venture forth into the Archives, and the regularly declassified technologies will remain widely undisclosed. Secrets remain safe because of indolence, apathy, and endless distractions.

It is evident that those who rule their geopolitical concerns have established a bureaucratic machine for systematically policing both those who research and those who venture. Information is power. The careful and meticulous bureaucratic examination of private business, and the movements of seemingly insignificant persons in their private ventures, irritates those who believe themselves "in control". True control requires no patrol, an overwhelming truth which reveals the insufficient state of heart. Bureaucracies grant privilege to private ventures until unexpected, possibly destabilizing potentials emerge. Always in this foil play are considerations of the very simplest kind, the maintenance of oligarchic control being the chief priority which dictates the movements of bureaucratic branches. Oligarchs fear the loss of control. They fear this loss because they recognize the fact that far more capable and incisive personalities can usurp their golden thrones.

In a Technological Age, gold is an insufficient means of control. If ideas were harmless, so much effort on suppressing them and their hardware embodiments would never have been exerted. The killing of dreams, of ideas, of ideals and aspirations is a theme far too overrated in the media. Those who have the most to lose from the application of very simple ideas are the most fearful of them. They must therefore promote the lie that ideas die...Blind power lust is often indiscreet. Nevertheless, ideas persist and rule principalities. The whisper of a thought is sufficient to topple kingdoms.

It also becomes increasingly clear that aggressive foreign conglomerates are ill-equipped to compete with such advanced systems as these. Third World forces will continue developing and relying upon obsolescent war technology, just as the NAO will continue developing and relying upon radiation technology. "Access" becomes the critical term in these regards. An ability to attain technological heights through access to the most highly regulated components in the world today defines one's position in the scale of war power. The spirit of hatred, that which fuels and drives humanity to destroy itself, will stop at nothing in achieving that wandering will. Those hostile and irrational Third World forces, who wage their international war of terrorism regardless of high-technology access, have not been prevented from accomplishing their foul intent. The question we must ask concerns the contradiction which exists, between having high-technology war power, and withholding its use. Why are those leaders, those branded as our avowed enemies throughout the media propaganda, necessarily yet alive? The answer to this single question will be far more revealing than all of our combined efforts and researches.

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BEAMRAY WEAPONS

June 25, 1957 L. REIFFEL 2,797,333

X-RAY SOURCE

Filed July 24, 1953

Fig. 1

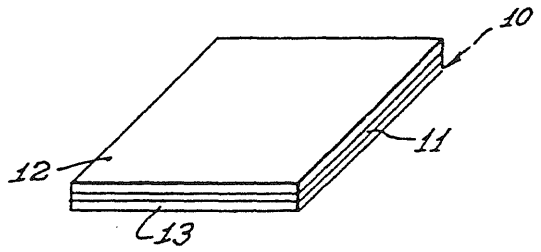


Fig. 2

Fig. 3

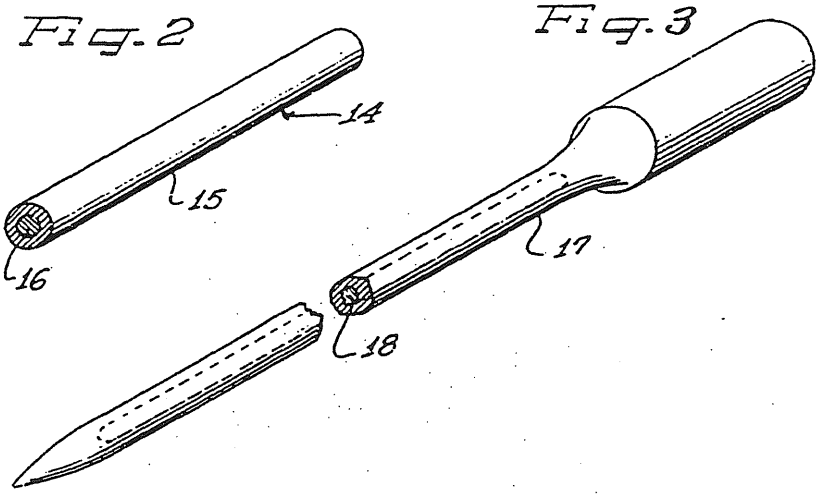


Fig. 4

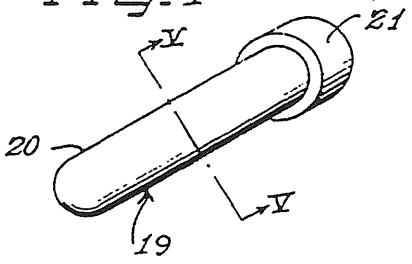
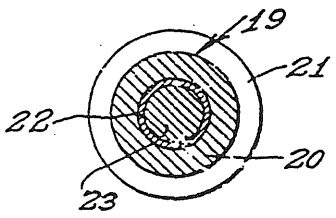


Fig. 5



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2,797,333

X-RAY SOURCE

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Application July 24, 1953, Serial No. 370,175

12 Claims. (Cl. 250—84)

This invention relates to a source of X-rays and, more particularly, to a source of X-rays including a source of beta particle emitting radioactive material and a target in conjunction therewith.

X-rays have heretofore been produced by X-ray tubes in which electrons are accelerated by use of a source of high potential and impinged on a target. The apparatus required is very bulky, complex and expensive to manufacture and maintain and the high potentials utilized are very dangerous.

This invention utilizes Bremsstrahlung which is radiation generated when high energy beta particles (electrons) are decelerated in the region of target nuclei. The theory underlying this effect has been known for many years but no practical use has ever been made of it. In fact, it has constituted mainly a nuisance and has been considered in practice only to the extent that shields and the like have been provided to prevent such radiation.

According to this invention, the Bremsstrahlung effect is utilized in an X-ray source which may preferably comprise beta particle emitting radioactive material in conjunction with a target.

It will be readily appreciated that this source may be very compact and yet efficient, safe, reliable and inexpensive. In addition, the intensity spectrum of the radiation produced is approximately flat from zero up to the energy of the incident beta particles so that a continuous spectrum of X-rays is produced which is desirable in many applications. Further, the invention makes possible the use of X-rays in applications where they have never before been utilized or where they have been utilized only to a very restricted extent, due to the limitations on the X-ray generating equipment previously used.

Any kind of beta particle emitting radioactive material is suitable. In most applications, the maximum energy of the beta particles should be at least 150,000 electron volts. The material may, or may not, emit alpha particles as well, since such slow moving particles will normally be readily absorbed by the target material. The radioactive material may, or may not, emit gamma rays. However, if the material does emit gamma rays, then the energy of the X-rays derived from impingement of the beta particles on the target should be at least one percent and, preferably, considerably more than 10 percent of the energy derived from the gamma rays.

The target may be of any desired material, gaseous, liquid or solid. However, in most applications, a target material having a relatively high atomic number will be preferred, since the efficiency of X-ray production is greater the higher the atomic number. Lead, tungsten and other heavy metals are particularly suitable.

According to another feature of the invention, the target is in surrounding relation to the radioactive material so that, in addition to acting to produce X-rays, it also acts as a shield preventing radiation of undesirable rays into the surrounding space. If desired, the target may be thicker on one side than another so as to prevent

any radiation from the one side and to direct X-ray radiation from the other side.

According to a further important feature of the invention, the target is of such a form that it has oppositely facing boundaries. For example, it may take the form of a plate having parallel boundary surfaces or a tube having inner and outer boundary surfaces. Means are provided for impinging beta particles against one of the boundaries which means may preferably comprise beta particle emitting radioactive material but might comprise a vacuum or gaseous conduction tube or the like.

It has been discovered that for maximum efficiency, the beta particles should have sufficient energy to penetrate to the region of the other of the boundaries from which the X-rays are emitted.

Accordingly, the spacing between the boundaries should be so related to the characteristics of the target and the energy of the beta particles that the range of the particles is to the vicinity of the aforesaid other boundary.

It might be here noted that with the conventional X-ray generator tubes, the X-ray radiation is from the same side of the target as that on which the electrons are impinged, while by this invention, the X-ray radiation is from a surface or boundary of the target opposite to that on which the beta particles are impinged.

With any particular type of target material and with any maximum given beta particle energy, there will, of course, be a particular penetration range which can be determined from known tables and formula or by preliminary tests made according to well-known test procedure, as will readily be understood by those skilled in the art.

If the beta particles penetrate appreciably farther than the boundary of the target, then they may penetrate appreciable distances into the surrounding space and may likely cause harmful effects. If the beta particles do not penetrate to the region of the boundary, then there will be appreciable absorption of the X-rays and decreased efficiency. Also, the process of producing the X-rays from impingement of beta particles on the target material is, by nature, reversible. Hence, X-rays produced may act on the target material beyond the range of penetration of the beta particles and cause a "secondary" emission of beta particles from the target which, of course, would be highly undesirable.

According to a specific feature of the invention, the X-ray source may take the form of a "sandwich" in which the radioactive material is placed between two sheets of target material of a thickness depending upon the range of beta particle radiation emitted.

According to another specific feature of the invention, the X-ray source may take the form of an intimate mixture of the beta particle emitting radioactive material and the target material as liquids or as powders.

According to a further specific feature of the invention, the X-ray source may comprise a target in the form of a tube with the beta particle emitting radioactive material therewithin. The thickness of the walls of the tube is, of course, dependent upon the range of the beta particles.

According to still another specific feature of the invention, the X-ray source may comprise a capsule of very thin plastic containing the beta particle emitting radioactive material and surrounded by a removable target. This X-ray source could be "turned off" by replacing the target with a beta radiation shield of considerable thickness.

According to a still further specific feature of the invention, the X-ray source may comprise a target in the form of a hollow needle in which the beta particle emitting radioactive material is disposed. This source might,

for example, be imbedded in a cancerous growth. The range of radiation and the long useful life obtainable from such a source make it particularly desirable for such a purpose.

It will, accordingly, be apparent that this invention provides a source of X-rays which is extremely compact, portable, readily used, inexpensive, safe and highly efficient.

An object of this invention, accordingly, is to provide an improved source of X-rays.

Another object of this invention is to provide an improved source of X-rays using radioactive material.

A further object of this invention is to provide an improved source of X-rays utilizing a beta particle emitting radioactive material surrounded by a target.

Still another object of this invention is to provide an improved X-ray source comprising a target having oppositely facing boundaries with means for impinging beta particles against one of the boundaries with sufficient energy to penetrate to the region of the other of the boundaries.

Other objects of the invention reside in the particular and highly advantageous arrangements of beta particle emitting radioactive material and targets.

This invention contemplates other objects, features and advantages which will become more fully apparent from the following detailed description taken in conjunction with the accompanying drawing which illustrates preferred embodiments and in which:

Figures 1, 2, 3 and 4 illustrated preferred embodiments of X-ray sources constructed according to the principles of this invention; and

Figure 5 is a sectional view through the embodiment of Figure 4, taken substantially along the line V—V.

In Figure 1, reference numeral 10 designates one preferred form of X-ray source constructed according to the principles of this invention. The source 10 is in the form of a "sandwich" in which beta particle emitting radioactive material 11 is placed between two sheets 12 and 13 of target material.

The thickness of the sheets 12 and 13 will be determined by the maximum energy of the beta particles emitted by the material 11 and the type of material used for the target sheets 12 and 13. This thickness should preferably be such that the beta particles will penetrate to the outer surfaces of the sheets 12 and 13. This thickness can be determined by known tables and formula or by preliminary tests made according to well-known test procedures.

As examples, the radioactive material 11 might be strontium 90 and the sheets 12 and 13 might be lead plates approximately 0.040 inch thick or platinum plates approximately 0.018 inch thick.

It will be understood that thinner plates might be used if beta particle emission is permissible or desirable while somewhat thicker plates might be used if it is desired to reduce the total energy of the X-rays or change the frequency spectrum of the X-rays emitted.

The radioactive material 11 must, of course, emit beta particles and the maximum energy of the beta particles emitted should preferably be at least 150,000 electron volts to obtain efficient production of the X-rays. The material may, or may not, emit alpha particles as well since such slow moving particles will normally be readily absorbed by the target.

The radioactive material 11 may or may not emit gamma rays. However, if it does emit gamma rays, then the energy of the X-rays derived from impingement of the beta particles on the target plates 12 and 13 should be at least one percent and preferably much more than 10 percent of the energy derived from the gamma rays.

It may be noted that the plates 12 and 13 are in generally surrounding relation to the radioactive material 11 so as to act as a shield in preventing undesirable radiations. If desired, the peripheries of the plates 12 and 13 might be joined so as to completely enclose the radioactive material.

In Figure 2, reference numeral 14 designates another preferred form of X-ray source according to the principles of this invention. The source 14 comprises a target 15 in the form of a tube with radioactive material 16 disposed inside the tube 15. The considerations involved in selecting the type of radioactive material 16 and the thickness of the walls of the tube 15 are generally the same as those involved in selecting the radioactive material 11 and the thickness of the plates 12 and 13 in the embodiment of Figure 1 as described above.

As an example, the tube 15 may be of platinum approximately 0.1 inch in diameter and 0.3 inch long with a wall thickness of 0.018 inch filled with one-half curie of strontium 90 and might be used in interstitial treatment of extensive malignancies. This would be appropriate for high level dosage, for extremely long times.

Another example would be the same tube filled with phosphorus 32 which could be used for shorter lived irradiation with approximately the same X-ray characteristics.

As a further example, silver 111 might be used in the same configuration.

Still another example would be calcium 45 which could be used for extremely low energy radiation for fairly long times of a year or so. With both silver 111 and calcium 45, the wall thickness of the tube 15 might be appreciably thinner than 0.018 inch, perhaps 0.005 inch.

The ends of the tube 15 might preferably be closed as to prevent radiation directly from the radioactive material 16. If desired, the general form of Figure 2 might take the form of a needle 17 as illustrated in Figure 3 with the needle forming the target and being hollow with radioactive material 18 disposed therewithin. With this form, the treatment of many types of malignancies could be readily effected.

In Figure 4, reference numeral 19 designates another preferred X-ray source according to the principles of this invention. The source 19 comprises a target having a hollow body portion 20 and a cap 21 removable disposed on one end of the body portion 20. Disposed within the body portion 20 is a capsule 22 of thin plasic material, or the like, which is filled with radioactive material 23. The walls of the capsule must, of course, be thin enough to readily pass the beta particles emitted by the radioactive material 23.

To "turn off" the source 19, the capsule 22 might be removed from the target and the target replaced with a shield of similar physical construction but having low atomic number and considerable thickness so as to effectively eliminate radiation.

Another preferred form of the invention, not illustrated, is an intimate combination of beta particle emitting radioactive material with target material, either as powders, gases, liquids, mixtures, alloys or compounds, or any combination thereof.

It will be understood that while certain preferred structural forms and certain preferred types and dimensions of materials have been set forth above, the invention is not limited thereto and various other physical embodiments, dimensions, and characteristics will be suggested by the teachings above.

It will further be apparent that this invention provides an X-ray source having extremely wide application which is extremely compact, portable, readily used, inexpensive, safe and highly efficient.

It will still further be understood that various modifications and variations may be effected without departing from the spirit and scope of the novel concepts of this invention.

I claim as my invention:

1. An X-ray generator, comprising: a target, and beta particle emitting radioactive material so disposed relative

to said target that the beta particles bombard target atoms to produce X-rays, the compositions and relative geometry of the radioactive and target materials being such that usable quantities of X-rays are radiated from the generator and comprise at least one percent of the total radiation from the generator.

2. An X-ray generator, comprising: a target, and beta particle emitting radioactive material so disposed relative to said target that the beta particles bombard target atoms to produce X-rays, the compositions and relative geometry of the radioactive and target materials being such that the energy radiated from the generator is predominantly in the form of X-ray radiation.

3. In an X-ray generator, beta particle emitting radioactive material, and target material in the path of the beta particles emitted by said radioactive material to substantially absorb said beta particles and generate X-rays through the bombardment of target atoms by the beta particles, the compositions and relative geometry of the radioactive and target materials being such that usable quantities of X-rays are radiated from the generator and comprise at least one percent of the total radiation from the generator.

4. In an X-ray generator, beta particle emitting radioactive material, and target material in the path of the beta particles emitted by said radioactive material to substantially absorb said beta particles and generate X-rays through the bombardment of target atoms by the beta particles, the compositions and relative geometry of the radioactive and target materials being such that the energy radiated from the generator is predominantly in the form of X-ray radiation.

5. An X-ray generator, comprising: a target having oppositely facing boundaries, and radioactive material for impinging beta particles against one of said boundaries with sufficient energy to penetrate to the region of the other said boundaries so that the beta particles bombard target atoms to cause emission of X-rays from said other of said boundaries, the compositions and relative geometry of the radioactive and target materials being such that usable quantities of X-rays are radiated from the generator and comprise at least one percent of the total radiation from the generator.

6. An X-ray generator comprising: an intimate combination of beta particle emitting radioactive material and target material such that the beta particles bombard target atoms to produce X-rays, the compositions and relative geometry of the radioactive and target materials being such that usable quantities of X-rays are radiated from the generator and comprise at least one percent of the total radiation from the generator.

7. An X-ray generator, comprising: a pair of sheets of target material, and beta particle emitting radioactive material arranged between said sheets so that the beta particles bombard target atoms to produce X-rays, the compositions and relative geometry of the radioactive and materials being such that usable quantities of X-rays are radiated from the generator and comprise at least one percent of the total radiation from the generator.

8. An X-ray generator, comprising a capsule of target material having beta particle emitting radioactive material

therewithin so that the beta particles bombard target atoms to produce X-rays, the compositions and relative geometry of the radioactive and target materials being such that usable quantities of X-rays are radiated from the generator and comprise at least one percent of the total radiation from the generator.

9. An X-ray generator, comprising: a capsule containing beta particles emitting radioactive material and having walls thin enough to readily pass the beta particles, and a target removably surrounding said capsule so that the beta particles bombard target atoms to produce X-rays, the composition and relative geometry of the radioactive and target materials being such that usable quantities of X-rays are radiated from the generator and comprise at least one percent of the total radiation from the generator.

10. An X-ray generator, comprising: a needle of target material, and beta particle emitting radioactive material within said needle so that the beta particles bombard target atoms to produce X-rays, the compositions and relative geometry of the radioactive and target materials being such that usable quantities of X-rays are radiated from the generator and comprise at least one percent of the total radiation from the generator.

11. An X-ray generator, comprising: a capsule containing beta particles emitting radioactive material and having walls thin enough to readily pass the beta particles, and a target removably surrounding said capsule so that the beta particles bombard target atoms to produce X-rays, the compositions and relative geometry of the radioactive and target materials being such that usable quantities of X-rays are radiated from the generator and comprise at least one percent of the total radiation from the generator, said target being replaceable with a shield having a lower atomic number and considerably greater thickness so as to effectively eliminate radiation.

12. An X-ray generator comprising: a target, and beta particle emitting radioactive material so disposed relative to said target that the beta particles bombard target atoms to produce X-rays, the compositions and relative geometry of the radioactive and target materials being such that usable quantities of X-rays are radiated from the generator and comprise at least one percent of the total radiation from the generator, the beta particles emitted from said radioactive material having a maximum energy of at least 150,000 electron volts.

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Sept. 15, 1959 W. GSCHEIDLEN 2,904,692

DEVICE FOR COLLIMATION OF A RAY BEAM

Filed Jan. 15, 1957 2 Sheets-Sheet 1

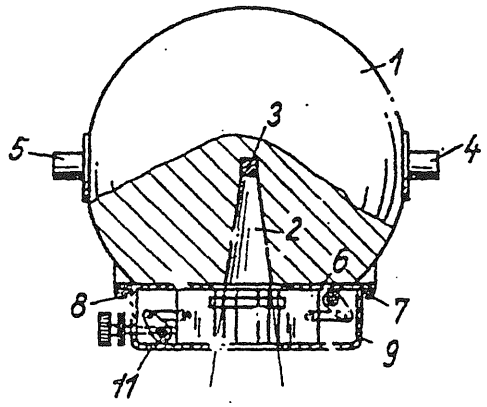

Fig. 1

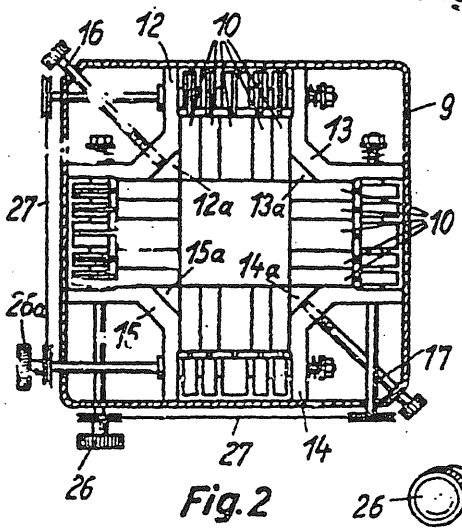

Fig. 2

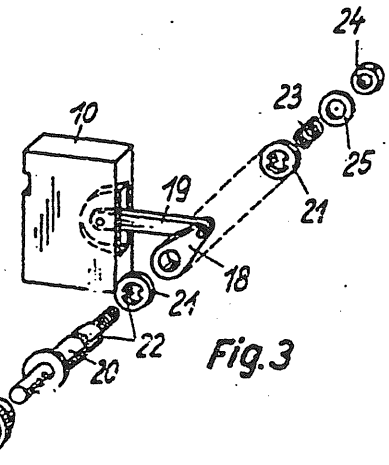

Fig. 3

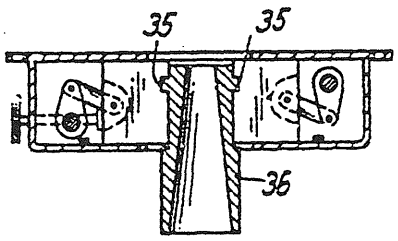

Fig. 9

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DEVICE FOR COLLIMATION OF A RAY BEAM

Filed Jan. 15, 1957 2 Sheets-Sheet 2

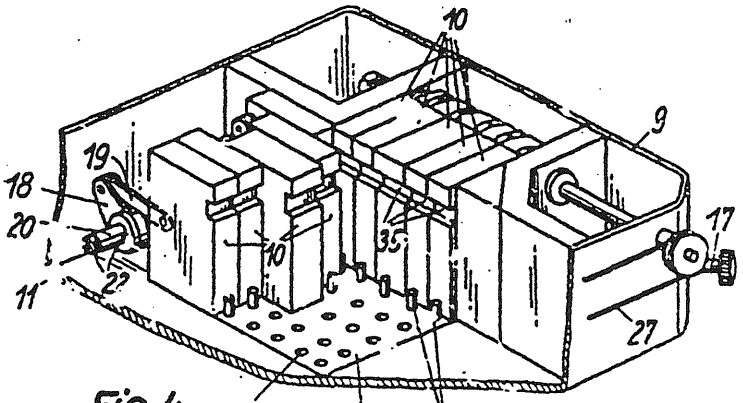

Fig. 4

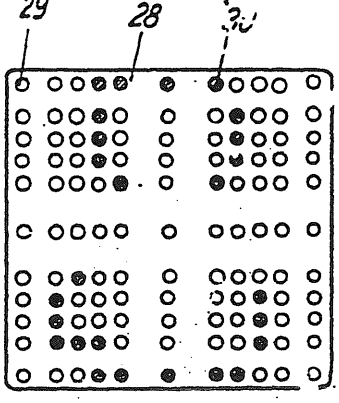

Fig. 5

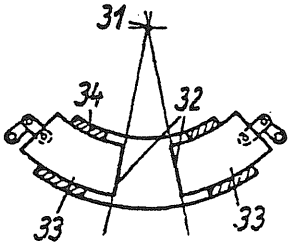

Fig. 7

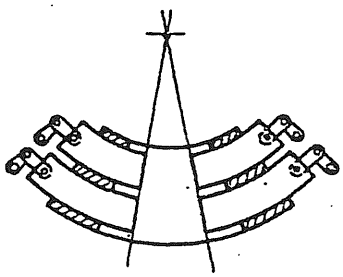

Fig. 8

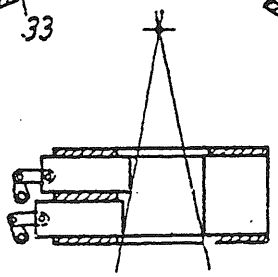

Fig. 6

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United States Patent Office 2,904,692 Patented Sept. 15, 1959

2,904,692

DEVICE FOR COLLIMATION OF A RAY BEAM

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Application January 15, 1957, Serial No. 634,195

Claims priority, application Germany January 21, 1956

6 Claims. (Cl. 250—105)

This invention relates to a device for collimation of a useful ray beam emanating from a source of high energy, for example cobalt 60, employing collimator plates that can be adjusted perpendicular to the central ray of the ray beam to be collimated. The usual collimator systems of this kind provide rectangular plates, which are arranged in pairs one above the other and positioned in planes perpendicular to the central ray of the ray beam in such manner that subsequent pairs of plates in the direction of the central ray are at right angles to each other. This stacked arrangement of the pairs of plates in the direction of the central ray necessitates a rather large size of the collimator system. In the direction of the central ray, subsequently arranged pairs of plates which limit the ray beam at their opposing sides are not directly stacked one above the other but arranged with a space between them. This space is occupied by a pair of plates disposed at right angle to the adjacent pair of plates and therefore limits the beam with the other opposing sides. Furthermore, this arrangement allows only the collimation of rectangular or quadratic fields.

According to this invention a plurality of groups of collimator plates which are approximately rectangular are positioned upright in the direction of the central ray of the ray beam and stacked perpendicular to the central ray, an adjusting member being provided for each collimator plate, and a driving element, a driving shaft for instance, which is common to the adjusting members of a group is coupled thereto via friction couplings only. Thereby, the following advantages are obtained:

The ray beam is laterally limited by the edge walls of the upright collimator plates. These limiting surfaces are not interrupted in the direction of the central ray. Consequently, this collimator system can be less in height than the usual collimator systems where the lateral limiting surfaces are interrupted in the direction of the central ray.

Since the power transmission from the common driving element to the individual adjusting members of a group is effected only by friction, it is possible to apply counter forces to the individual collimator plates when the common driving element is actuated, which counteract the frictional force between the driving element and the adjusting member for the individual collimator plate.

Such counter forces may be produced, for example, by means of stops for the individual collimator plates. If such counter forces are not applied, all collimator plates will be moved when the driving element for the corresponding group of plates is actuated. Stops may be provided for individual plates, so as to exclude such plates from the common adjustment operation, either along the complete range of adjustment or a part thereof. It is in this manner possible to limit the useful ray beam so as to obtain desired shapes and sizes of fields.

The foregoing and further features and objects of the invention will appear from the following description of

examples which will be rendered below with reference to the accompanying drawing. In the drawing,

Fig. 1 shows a radiation head partly in section and partly in elevation;

Figs. 2 to 4 show various views of the collimator system;

Fig. 5 illustrates a template for setting the field;

Fig. 6 indicates in schematic manner a plurality of collimator systems one disposed upon the other in the direction of the central ray beam;

Fig. 7 shows arcuate plates arranged in planes parallel to the central ray;

Fig. 8 indicates a plurality of collimator systems according to Fig. 7, arranged in superposed manner; and

Fig. 9 indicates the use of a treatment cone in conjunction with a structure such as shown in Fig. 4.

The radiation head, shown in Fig. 1, comprises a spherical shielding body 1, which is provided with a radial, conical or pyramidal shaped cutout 2 extending substantially to the center of the head, where the source 3, cobalt 60 for instance, is disposed. The radiation head may be rotatably mounted by means of diametrically disposed pivots 4, 5.

The shielding body 1 is provided with a plane surface 6 located on the lower side as shown in the drawing, to which is secured a collimator system 9 by means of the screws 7, 8.

The collimator system 9 illustrated in Figs. 2 to 4 comprises a plurality of groups of collimator plates 10, extending upright in the direction of the central ray of the ray beam and in the respective groups side by side in planes parallel to the central ray of the ray beam the edges of the plates facing in directions perpendicular to the central ray. In the example shown, the plates are combined in two pairs of groups, each group having five plates. The base 11 of the casing of the collimator system serves to guide the plates. The groups of plates are confined in their positions by means of angle bars 12, 13, 14, 15 and prism-shaped blocks 12*a*, 13*a*, 14*a* and 15*a*, which may be adjusted manually with the screw-spindles 16, 17, thus making it possible to vary the contact pressure between the collimator plates.

As shown in Fig. 3, the adjusting means for the collimator plates comprises an adjusting crank 18 for each corresponding plate, with a push rod 19 articulated with the plate. All cranks 18 belonging to a group of plates are rotatably mounted on a common driving shaft 20. The rotation of the cranks 18 is effected with the aid of friction disks 21 carried by the shaft 20, by means of grooves and tongues, for example, and pressed against the cranks 18 by springs 23. The spring pressure may be varied by means of an adjustable nut 24 on the shaft 20 operating against a washer 25 which engages the spring. The shaft may be adjusted by means of knob or handwheel 26 which is fastened thereto. As will be seen from Fig. 2, the collimator plates of oppositely disposed groups are commonly adjustable. For this purpose, the two driving shafts which operate the corresponding groups of plates are coupled to each other by means of an endless belt 27 or the like. Fig. 2 shows the operating means 26 and 26*a*, each for adjusting two groups of oppositely disposed plates.

In order to set the field, a setting template 28 may be employed as illustrated in Fig. 5 (also shown in Fig. 4), which is provided with a number of bores 29, for receiving pins or similar stop means. Since the cranks 18 are rotatably mounted on the shaft 20 and are moved on account of the frictional forces between the cranks and the friction disks 21, the collimator plates may be brought into positions which are limited by the pins 30 of setting template 28. It is thus possible to set the shape and

size of the field in steps corresponding with the number of plates contained in each group.

In the case of very high radiant energies it may be advantageous to arrange several collimator systems of this type, one above the other, in the direction of the central ray, as schematically outlined in Fig. 6. In such arrangement, the adjusting means for superposed groups of plates may be coupled analogously as described below. One setting pattern with adjustable stops may be provided for each collimator system, so that the setting of the field size and shape may again be effected as previously explained.

According to Fig. 7, arcuate collimator plates 33 arranged in planes parallel to the central ray and supported so that they may be swivelled about an axis 31, which preferably extends through the radiation source, the front edges 32 of the collimator plates 33, extending tangential to the ray beam and forming limiting surfaces therefor. Numeral 34 indicates curved guide tracks for the plates 33.

As shown in Fig. 8, two or more collimator systems, such as indicated in Fig. 7 may be superposed in the beam direction. The adjusting means may correspond to those previously described.

As illustrated in Fig. 4, the collimator plates can be provided with groove-shaped cutouts 35, into which, according to Fig. 9, a treatment cone 36 may be inserted, which is of advantage in order to reduce the penumbra zone of sources with larger focus areas.

The ray beam may be partially limited by fixed, upright bodies, for instance, bodies of U-shaped cross section, with a stack of collimator plates arranged in the interior space thereof to limit a portion of the ray beam according to shape and size. If two opposing stacks of collimator plates are utilized, they may be movably supported between fixed limiting bodies. Such and similar arrangements are within the scope of this invention. Moreover, it is possible to couple not only the driving elements for two oppositely disposed groups of plates, but those for any number of groups of plates, if necessary those for all groups of plates, and to operate them by a common actuating means.

What I claim is:

1. A device for collimating a ray beam emanating from a source of high energy, comprising a plurality of individually movable approximately rectangular collimation plates disposed side by side in upright positions with corresponding edges thereof extending in the direction of the ray beam to be collimated, said edges constituting the collimating edges, and a separate adjusting member for each of said collimator plates adapted to move its respective plate laterally in a direction perpendicular to the ray beam to adjust the collimating edge thereof with reference to said ray beam, a common driving element for said adjusting members, and friction clutch means for coupling each individual adjusting member with said driving element.

2. A device according to claim 1, comprising a rotatable drive shaft constituting said common driving element, said adjusting members being freely rotatable upon said common drive shaft, said friction clutch means being fixedly mounted on said drive shaft, one friction clutch means for each adjusting member and disposed adjacent thereto.

3. A device according to claim 2, comprising spring means disposed on said shaft for exerting pressure axially thereof to effect friction pressure engagement of said friction clutch means with the adjusting members which are respectively individual thereto.

4. A device according to claim 1, comprising setting means for adjustably setting the adjustment pattern of said collimator plates with respect to the ray beam, said setting means comprising a template having rows of holes formed therein for receiving stops to be placed in the lateral paths of adjustment motion of the respective collimator plates for the purpose of selectively setting said collimator plates in accordance with a desired size and shape of the radiation field of the ray beam.

5. A device for collimating a ray beam emanating from a source of high energy, comprising a plurality of groups of collimator plates disposed at right angle to one another, each group comprising a plurality of individually movable approximately rectangular plates disposed side by side in upright positions with corresponding inner edges thereof extending in the direction of the ray beam to be collimated, a separate adjusting member for each plate in each group and adapted to move its respective plate laterally inwardly in a direction perpendicular to the ray beam to set the inner edge thereof with reference to such ray beam, a common driving member for the adjusting members in each group of plates, friction clutch means for coupling each individual adjusting member with the common driving member therefor, and means for coupling at least two of said driving members for common driving operation.

6. A device according to claim 5, comprising setting means for adjustably setting the adjustment pattern of the inner edges of said collimator plates with respect to the ray beam, said setting means comprising a template having rows of holes formed therein for receiving stops to be placed in the lateral inward adjusting path of motion of the respective collimator plates for the purpose of selectively setting said plates in accordance with a desired size and shape of the radiation field of the ray beam.

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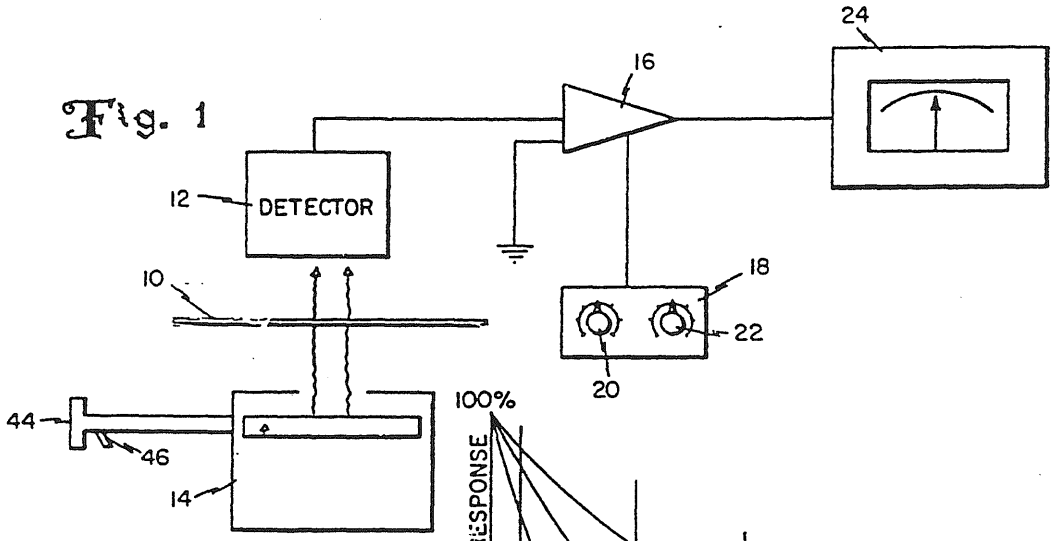
CONVERTIBLE RADIATION SOURCE

Filed Oct. 30, 1957 3 Sheets-Sheet 1

Fig. 1



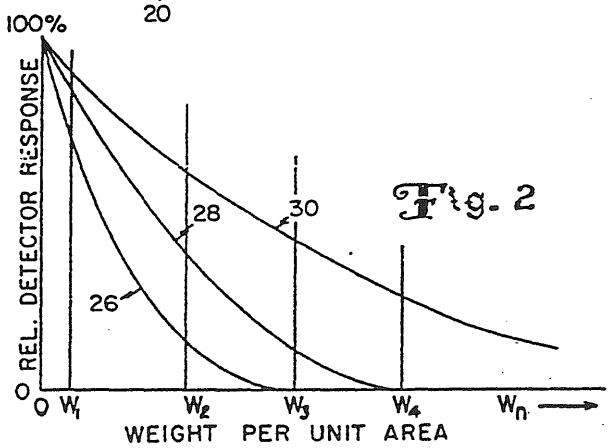


Fig. 2

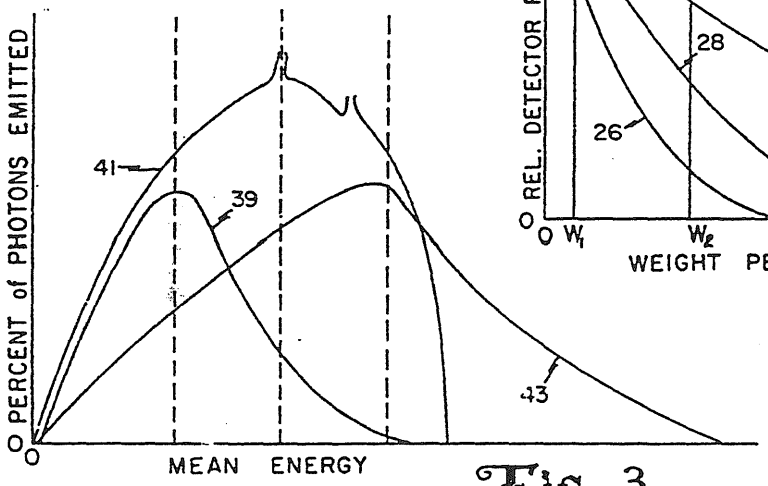


Fig. 3

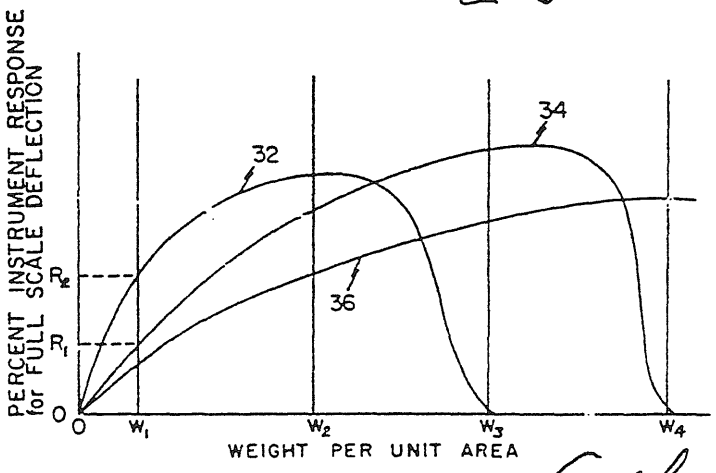


Fig. 4

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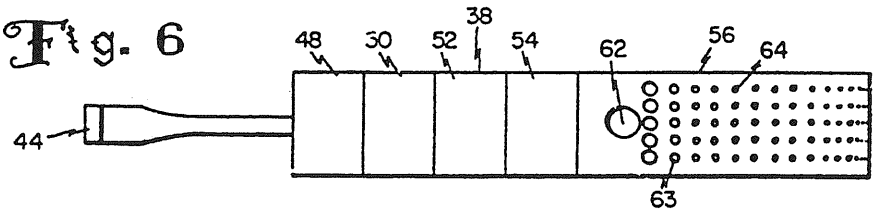
CONVERTIBLE RADIATION SOURCE

Filed Oct. 30, 1957 3 Sheets-Sheet 2

Fig. 6



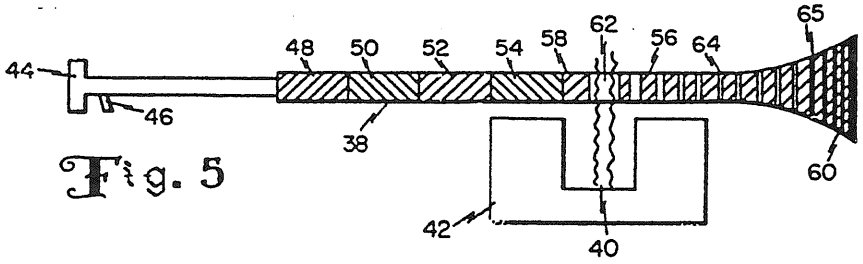


Fig. 5

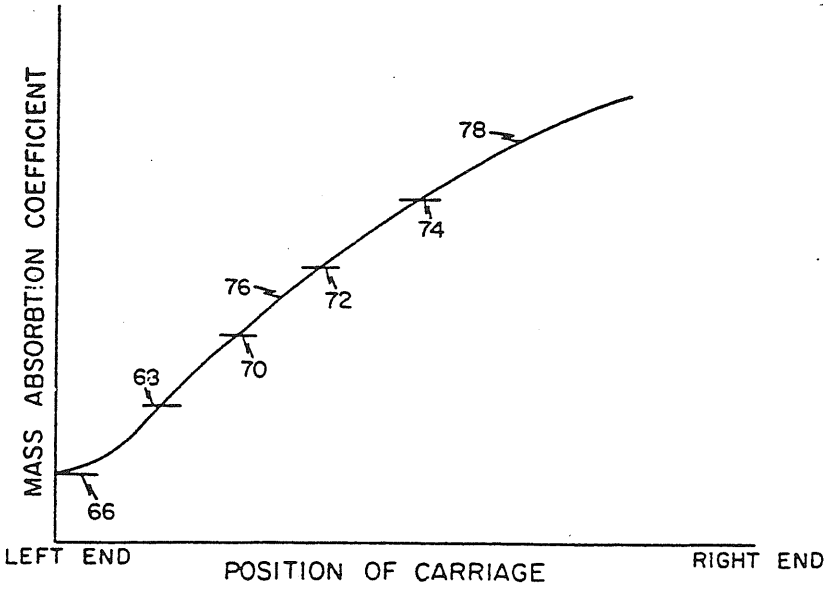


Fig. 7

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Sept. 12, 1961 G. B. FOSTER 2,999,935

CONVERTIBLE RADIATION SOURCE

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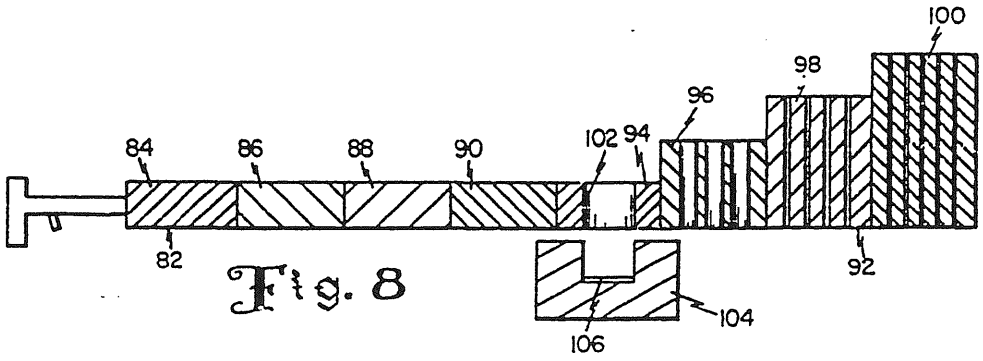

Fig. 8

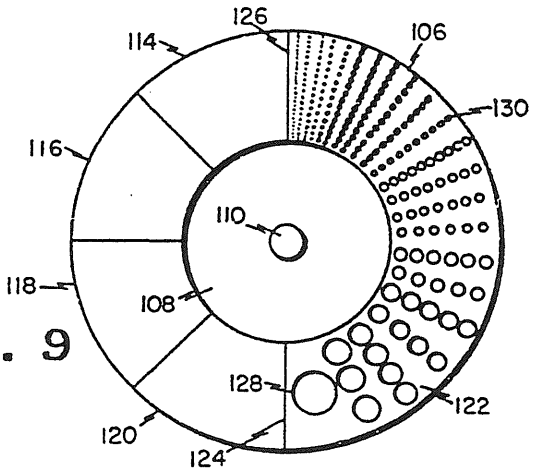

Fig. 9

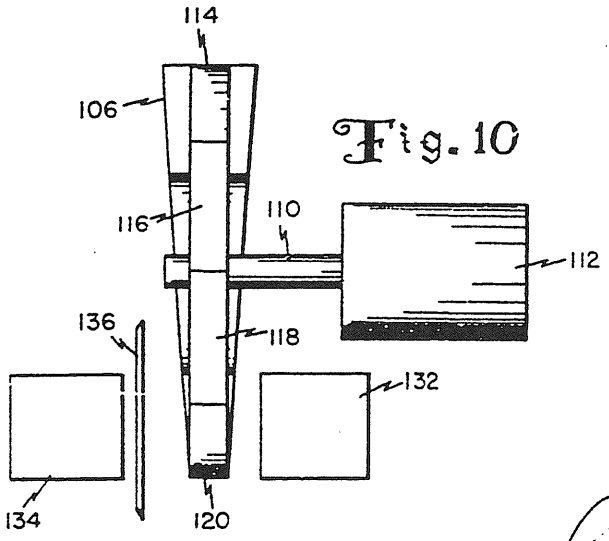

Fig. 10

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United States Patent Office 2,999,935 Patented Sept. 12, 1961

2,999,935

CONVERTIBLE RADIATION SOURCE

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Filed Oct. 30, 1957, Ser. No. 693,290
5 Claims. (Cl. 250—83.3)

This invention relates to a method and apparatus for radiation technique measurements of density and various other characteristics of materials. More particularly the invention relates to a method and apparatus for providing optimum radiation energy for the accomplishment of a wide range of measurements on various materials by radiation absorption and reflection methods.

The measurement of thickness, weight, density, profile and a wide range of other characteristics of materials through the use of radiation gauges disposed in various geometric relationships has become quite common and both X-ray tubes and radioactive sources have been used. Commercial X-ray equipment, however, is expensive, bulky, complicated to operate, and requires a certain amount of servicing. In addition, the intensity of the radiation produced by such equipment is less stable than the intensity of radiation emitted by radioisotopes.

On the other hand, measuring devices using radioactive sources of radiations, such as radioisotopes, have been limited in their usefulness because compromises must be made in the selection of the energy of the radiation source with relation to the range of materials to be measured with that source. That is to say, the designer of measuring devices using radioisotopes is limited in his selection of mean energies of radioactive radiations by considerations of cost, availability and half-lives of radioactive isotopes. While practical radioisotopes are available for emitting high energy gamma rays to provide all of the penetrability desired, the manufacturing, handling and storage of the capsules containing such gamma ray emitters requires extreme precautions and expensive facilities.

Several methods have been suggested for modifying or influencing the nature of the emanations which are ultimately used in making the desired measurements. Thus Atchley in United States Patent No. 2,629,831 shows a reflective method of obtaining attenuated beta radiation. Foster et al. in copending application Serial No. 434,786, filed June 7, 1954, now Patent No. 2,933,606, show a method of increasing the penetrability of primary beta radiation. Baldwin Instrument Company et al. in British Patent 689,857 of April 8, 1953, show a fixed collimation system using a pair of collimating filters. Also numerous workers have shown nulling gauging systems using absorbing wedges to attenuate radiation. Examples of such systems may be found in United States Patents Nos. 2,586,303 to Clarke and 2,678,399 to Fay.

While these prior methods increase the range of mean energy levels available to the equipment designer over and above the energies available by reason of the radioactive disintegration action alone, they still restrict him to the use of the particular type of energy source and the particular energy which he has selected. Gauges designed to use such sources are thus restricted in usefulness to the results obtainable through the use of the selected energy alone.

It is accordingly a primary object of this invention to provide a method and apparatus for making measurements through the use of radiation techniques which eliminates restrictions on equipment performance dictated by the radiation source and/or the sensitivity of the read-out device.

It is another object of the invention to provide a radiation technique method and apparatus for measuring a range of characteristics of materials greatly in excess of that possible with any prior equipment.

It is another object of the invention to provide a radiation technique measuring apparatus capable of performing the foregoing functions at a lower cost than would be possible with any collection of previously available equipment.

It is still another object of the invention to provide a device capable of producing a large variety of radiation energy spectra, or a large range of mean radiation energies, utilizing but a single radioactive source.

It is another object of the invention to provide a source of corpuscular radiations having a continuously variable mean energy of radiation.

It is still a further object of the invention to provide a method and apparatus of the foregoing type which permits a measurement of an extremely wide range of energy translating properties of materials.

These and further objects and advantages of the invention will become apparent upon reference to the following specification and claims and appended drawings wherein:

FIGURE 1 is a schematic representation of a radiation measuring device, such as a thickness gauge, employing one embodiment of the present invention;

FIGURE 2 presents a series of calibration curves obtained using the apparatus of FIGURE 1 and depicting the relative response of the detector and read-out device as a function of the thickness of the material being gauged;

FIGURE 3 is a graph showing radiation energy spectra corresponding to the energy translating characteristics shown in FIGURE 2;

FIGURE 4 is a graph showing percent instrument response necessary to obtain full scale meter deflection, a function of sensitivity, plotted against weight per unit area or material thickness for the three calibration curves shown in FIGURE 2;

FIGURE 5 is a side elevation of an apparatus for obtaining a large number of radiation energy spectra characteristics from a single primary source of radiation;

FIGURE 6 is a plan view of the apparatus of FIGURE 5;

FIGURE 7 is a graph showing the mass absorption coefficient of a given material plotted against the position of the movable member of the device shown in FIGURES 5 and 6.

FIGURE 8 is a vertical section of another embodiment of an apparatus for obtaining a large number of radiation energy spectra characteristics from a single primary source of radiation;

FIGURE 9 is an elevation of still another embodiment of an apparatus for obtaining a large number of radiation energy spectra characteristics from a single primary source of radiation; and

FIGURE 10 is a side view of the apparatus of FIGURE 9.

Referring to FIGURE 1, which shows one embodiment of a device employing the present invention, a material 10, some characteristic of which is to be measured, is placed between a radiation detector 12, such as an ionization chamber, and a source of radiation generally indicated at 14. For purposes of illustration it is assumed that it is desired to measure the thickness of the material.

The radiation flux received by the radiation detector 12 is translated into an electrical signal and this is fed to an amplifying means 16. A measuring device 18 is associated with the amplifying means 16 and is provided with a control 20 for setting the operating point of the amplifier corresponding to a particular weight of material to be measured. Measuring device 18 also contains a sensitivity control 22 for adjusting the response of the indicating device to the span of variation of the measured characteristic of the material to be measured. The meas-

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urement information is presented or indicated on a read-out device or meter 24 which is of the center scale zero type. A gauging system of this nature is described in detail in the copending application of Henry R. Chope, Serial No. 286,220, filed May 5, 1952, now U.S. Patent No. 2,829,268.

Such a measuring device 18 is of the null balance type wherein the control 20 adjusts a bucking signal so that the read-out meter 24 reads the difference between the bucking signal and the amplified version of the signal from the detector 12. The ordinate of the graph of FIGURE 2 thus may represent the position of control 20 between its two extremes, which are represented upon the graph as zero and 100%. For any thickness of material within the range of the instrument there is some setting of control 20 which causes the meter 24 to read zero. This setting is an indication of the relative response of the detector.

It will be apparent to those skilled in the art that a calibration or absorption curve can be prepared relating relative detector response to material thickness. With such an absorption curve available, the unknown thickness of a sample can be quickly determined by placing the sample in the gauge, adjusting the control 20 until the meter 24 reads zero, and reading the thickness from the point on the absorption curve which corresponds to the setting of control 20. Sample calibration or absorption curves are shown in FIGURE 2.

While maximum accuracy is obtained in this manner it is generally desirable to calibrate the instrument so that the scale of the meter 24 is direct reading over a practical range of thickness, making it unnecessary to readjust the control 20 or to refer to the absorption curve when measuring thickness within that range. It is in order to perform this function that the sensitivity control 22 is provided. This control adjusts the response of the meter 24 to a given voltage variation from the null balance condition. That is to say, if it is desired to measure a certain specified span or range of thickness (or other property) of some particular material, a certain variation in relative detector response is available. The sensitivity control 22 makes it possible to spread this variation over the entire scale of the meter 24. In other words, the range of thickness is spread over full scale of meter 24.

It will be obvious that if the span or range of weights to be measured is excessively large, this direct reading arrangement will introduce an error due to the non-linearity of the absorption calibration curve. Further, as a practical matter, the span of a weight range is also limited by the fact that it is normally desired to be able to read the meter to three digits.

It will also be apparent that there are practical limits on the minimum span of weight range as a result of certain statistical noise signals generated in the device. That is to say, at excessive weight range spans the statistical noise to signal ratio becomes excessive or, expressed in other words, the noise level becomes objectionable when the sensitivity is increased too much.

In order to facilitate an understanding of the characteristics of a measuring system of this type let it be assumed that the sensitivity control is set to provide a span equal to a given percentage of the center span thickness or weight per unit area to be measured. That is to say, for a center span thickness of 10 the full scale meter deflection corresponds to a weight per unit area span of 9.5–10.5. This provides a uniform percentage of accuracy when comparing the reaction of the measuring device to different center span thicknesses.

Let us assume, without further description for the time being, that the radiation source 14 is capable of producing a plurality of different radiation energy spectra, and that the detector and measuring instrument have been calibrated for three of these spectra as shown by the curves 26, 28 and 30 in FIGURE 2. Radiation energy

spectra curves which correspond to the absorption curves 26, 28 and 30 are shown in FIGURE 3 at 39, 41 and 43.

Referring to FIGURE 2, there are shown four weights or thickness W_1, W_2, W_3, and W_4 which it is desired to measure. Using these weights as center span weights, let it be assumed that the weight span of the measuring device in measuring each weight is 10 percent of that weight. The sensitivity control 22 is then set to spread this weight span over the full scale of meter 24. As examples: if W_2 is 100 the weight span is 10 and meter 24 reads from 95 to 105. If W_1 is 1 the weight span is 0.1 and meter 24 reads from 0.95 to 1.05.

It will be apparent to those skilled in the art that in order to obtain good instrument accuracy a relatively high relative detector response is desirable for the particular span or range being measured. If the slope of the absorption curve is too low at the center span weight the relative detector response is also low and poor accuracy results. Using spans equal to 10 percent of the center span weight, as discussed hereinabove, the relative detector response available for any given center span weight can be determined graphically from the absorption curves of FIGURE 2.

Consider, as an example, a weight of 100. As pointed out previously the span is 10 percent of this, or 10, and the low and high span weights are 95 and 105. Entering the abscissa in FIGURE 2 with a weight of 105, a relative detector response is obtained for the particular absorption curve in use. Let us call this the high scale relative detector response. A low scale relative detector response can similarly be obtained by entering the abscissa of FIGURE 2 with a weight of 95. If now the low scale relative detector response is subtracted from the high scale relative detector response the relative detector response span is obtained. Since the sensitivity control is set to spread this relative detector response span over full scale, the relative detector response span may also be referred to as the percent instrument response for full scale deflection. When the percent instrument response for full scale deflection is too low instrument sensitivity is set too high and instrument readings are inaccurate for the reasons pointed out hereinabove. A high percent instrument response for full scale deflection is thus desirable. The percent instrument response for full scale deflection for absorption curves 26, 28 and 30 has been plotted in FIGURE 4 as curves 32, 34 and 36 respectively.

Consider now the three calibration curves 26, 28 and 30 in FIGURE 2 and a measurement of the weights W_1, W_2, W_3, and W_4. It is readily apparent that the quantity W_4 cannot be successfully measured by means of the absorption curve 28 inasmuch as this weight of material is simply too thick to permit sufficient radiation flux to reach the detector. Stated in another manner, the slope of curve 28 is insufficient at W_4 so that the percent instrument response achieved is substantially zero as shown by curve 34 in FIGURE 4. This corresponds to an infinite sensitivity and if any signal at all is obtained it is completely unreliable because of the statistical signal to noise ratio.

Considering measurement of the quantity W_1, it will be apparent that the absorption curve 28 is not very satisfactory because of the small percent instrument response which must be utilized in order to obtain full scale deflection of the meter. This is shown at R_1 in FIGURE 4. Stated another way, the slope of curve 28 is insufficient at this low weight and the relative response of the detector must be spread out excessively so that the signal to noise ratio renders the reading unsatisfactory.

While absorption curve 28 could not satisfactorily be utilized to measure the quantities W_1 and W_4, it can, however, be quite satisfactorily utilized to measure the quantities W_2 and W_3. Thus turning to FIGURE 4 it will be seen that a relatively high percent instrument re-

sponse for full scale deflection is obtained with curve 34 for both W_2 and W_3.

While the quantity W_1 could not be satisfactorily measured using the absorption characteristic shown by curve 28, this quantity can be effectively measured by using an absorption characteristic such as that shown at 26 in FIGURE 2. Turning to FIGURE 4, wherein the percent instrument response for full scale deflection is plotted against weight per unit area, it will be seen that the percent instrument response R_2 obtained with curve 32 (corresponding to curve 26 in FIGURE 2) is almost double the percent instrument response R_1 obtained for this same weight with curve 34 (corresponding to curve 28 in FIGURE 2). This same absorption characteristic 26 in FIGURE 2 (curve 32 in FIGURE 4) can be quite effectively used to measure the quantity W_2. The absorption characteristic 26, however, obviously could not be utilized to measure the quantity W_4.

While W_4 could not be satisfactorily measured by either absorption characteristics 26 or 28, this quantity can be measured by absorption characteristic 30 in FIGURE 2. Turning to FIGURE 4 it will be seen that the percent instrument response curve 36 corresponding to absorption characteristic 30 in FIGURE 2 gives a very adequate percentage instrument response at the weight W_4. Absorption characteristic 30 can also be used to measure the weight W_3 and is almost as accurate as absorption curve 28 (percent response curve 34) for that purpose. On the other hand, absorption characteristic 30 could be used to measure quantity W_2 but its performance in so doing would not be as satisfactory as would absorption characteristic 26 (percent response curve 32).

It will thus be apparent that if a radiation source capable of producing a plurality of different radiation energy spectra was available, a single gauge would be capable of measuring a large range of properties and would be able to measure such properties with a much higher degree of accuracy than has heretofore been possible. Referring to FIGURES 5 and 6 there is shown a device for providing such a radiation source. An elongated carriage or target assembly 38 is mounted for longitudinal sliding movement over a radioactive beta emitting source 40 mounted in a collimating capsule 42. A handle, such as the handle 44, is provided for sliding the target assembly and a suitable locking means 46 is provided to lock the target assembly in position between movements.

The target assembly consists of a plurality of different materials 48, 50, 52 and 54 which are joined together in any suitable manner and which have a tapered wedge shaped member 56 attached thereto. The wedge shaped member 56 has an end 58 of the same cross section as the last material 54, to which it is attached, and is provided with a large aperture 62 in this end. The other end of this member is bell shaped, as shown at 60, and a large number of holes 64 pierce this bell shaped end. The holes 64 decrease in diameter from a maximum adjacent hole 62, to a minimum at the bell shaped end 60. An increasing number of holes per unit of area is provided as the bell shaped end is approached.

The materials 48, 50, 52 and 54 are used as bremsstrahlung radiation generators by reason of their placement in the path of the beta radiation flux emitted by the radioactive beta emitting source 40. As is taught in the aforementioned Foster et al. application, Serial No. 434,786, filed June 7, 1954, the mean energy of the secondary radiation generated within the material exposed to the primary beta radiation is a function, among other things, of the target material itself, particularly its atomic number. Target materials 48, 50, 52, 54 and 56 of various types may be used, including, as examples, lead, carbon, aluminum, iron, copper, etc. Preferably each target material 48, 50, 52 and 54 is sufficiently thick to stop 98% of the beta rays which would otherwise reach the material to be measured.

While the target materials themselves 48, 50, 52, 54 and 56 have discrete boundaries therebetween, the target assembly or carriage 38 is so mounted that its positions are not restricted to discrete locations corresponding to the segmental length of these materials. The target assembly may be positioned at any point along its longitudinal travel so that the primary beta radiation may impinge upon varying portions of two materials at the same time, thereby generating a net mean photon energy of resulting radiation which lies between the two energies which would result by irridation of either of the two materials alone.

Referring to the wedge shaped member 56, it will be seen that the thickness of the member increases as its end 60 is approached. Parallel holes 64 are provided and these progressively increase in number and decrease in diameter as the end 60 of the member is approached. The radiation produced by the source 40 is inherently a multidirectional radiation directed in all directions within the 180° defined by the horizontal plane which is the floor of the capsule 42. Some collimation is provided by the capsule, but the beta rays emanating therefrom are not completely parallel. When the large aperture 62 overlies the beta source 40 in capsule 42, very little additional collimation is effected so that the radiation emanating from aperture 62 possesses basically the same mean energy as the radiation emanating from the capsule. When the wedge shaped member is moved to the left in FIGURE 5, a series of apertures 63 overlie the source 40. The diameter of these apertures is less than that of aperture 62 and the total area of the apertures overlying the source 40 is reduced. This effects an additional collimation and reduces the mean energy of primary beta radiation emanating from the upper portion of the wedge shaped member 56. As the wedge shaped member is moved still farther to the left in FIGURE 5, a larger number of even smaller apertures 65 are brought into registry with the aperture in capsule 42. In addition to this the thickness of the wedge is increased so that additional collimation is effected both through the reduction in aperture size and the length of the collimating apertures. This results in an additional lessening of the energy of primary beta radiation passing through the wedge shaped member. It will thus be seen that while the portion of the carriage 38 comprised of materials 48, 50, 52 and 54 acts as a bremsstrahlung generator, the wedge shaped member 56 does not, but acts as a variable collimating device producing primary beta radiation of varying mean energy. Section 56 need not necessarily be of a varying thickness if varying diameter apertures are used, although this provides an additional variation in collimation: nor do the apertures have to be of varying diameter if a thickness variation is used. A graduated degree of collimation is desired and this may be effected by any suitable means, such as a variation in aperture diameter or wedge thickness or both.

FIGURE 7 shows a relationship obtained with a certain set of materials wherein the effective mass absorption coefficient resulting from irradiation of the various materials is plotted against the position of the target assembly or carriage 38. In such an arrangement the secondary radiation is allowed to emit from an orifice in the source 14 (FIGURE 1), passes through the material to be measured and is detected by the detector 12. The horizontal line 66 in the graph indicates the mass absorption coefficient obtained when the primary beta source 40 irradiates only the material 48. The horizontal lines 68, 70 and 72 likewise represent the mass absorption coefficients obtained when the primary beta radiation source irradiates target materials 50, 52 and 54, respectively. By adjusting the size of the collimating aperture in the capsule 42, which contains the primary beta radiation source 40, and the width of the target materials 48, 50, 52 and 54, it is possible to provide a relatively smooth change in the mass absorption coefficient as the position of the carriage

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or target assembly 38 is varied, as is shown by curve 76 in FIGURE 7. While such a smooth curve may be obtained it will be recognized by those skilled in the art that this is by no means essential and that stepped characteristics may be used.

The horizontal line 74 in FIGURE 7 represents the mass absorption coefficient obtained when the aperture 62 in member 56 is adjacent the primary beta radiation source 40 and the radiation used is primary radiation. As the right end of the target assembly comprising the bell shaped member 64 is moved over the primary beta radiation source, primary beta radiation is used and a further variation in mass absorption coefficient is obtained through the varying depth and diameter of the collimating holes 64. By utilizing a sufficiently large number of holes and providing for a gradual variation in their diameters and in the thickness of the member 56, a smooth mass absorption coefficient curve 78 can be obtained as the position of the carriage or target assembly is changed. As pointed out hereinbefore it is not essential that this curve be smooth.

The target materials 48 and 50, as an example, may produce energy absorption spectra such as those shown at 39 and 43 in FIGURE 3. When the large hole 62 in member 56 is positioned over beta source 40, a beta radiation spectra such as that shown at 41 in FIGURE 3 may result. Since the target assembly or carriage is capable of movement to any position over the source of primary beta radiation 40, an infinite number of intermediate energy absorption spectra may be obtained.

While the carriage or target shown in FIGURE 5 utilizes a bell or wedge shaped end portion 56 and varying diameter apertures it will be apparent to those skilled in the art that other variable collimating arrangements may be used. One example of such an arrangement is shown in FIGURE 8. Referring to that figure, a carriage or target 82 is comprised of a plurality of target materials 84, 86, 88 and 90 of different atomic numbers as in the preceding embodiment of the invention. Attached to these elements is a stepped collimating member 92 having stepped portions 94, 96, 98 and 100 of different thicknesses. The minimum thickness portion 94 is provided with an aperture 102 of substantially the same diameter as the aperture in the capsule 104 containing source 106. The succeeding portions 96, 98 and 100 are provided with increasing numbers of apertures of the same size. An even further degree of collimation may be obtained if these latter apertures are of decreasing diameter.

For FIGURES 9 and 10 there is shown a still further embodiment of the invention wherein the movement of the carriage or target is rotary rather than reciprocating as in the preceding embodiments. Referring to these figures, there is shown a circular target 106 consisting of a hub 108 mounted on a shaft 110 which may be driven either by hand or by an automatic means such as a servomotor 112. Mounted on the hub 108 are a plurality of elements 114, 116, 118 and 120 of different atomic numbers which coincide with the elements 48, 50, 52 and 54 of the device in FIGURE 5. The remainder of the periphery of hub 108 has an arcuate member 122 attached thereto and this member increases in thickness from its juncture with element 120 at 124 to its juncture with element 114 at 126. A large aperture 128 is provided adjacent element 120 and juncture 124 and a progressively increasing number of apertures 130 of decreasing diameter is provided between aperture 128 and juncture 126 and element 114. The increasing thickness of arcuate section 122, as best seen in FIGURE 10, provides increasingly long collimating apertures as juncture 126 is approached.

A radiation source 132 is provided adjacent one face of the circular target 106 and a suitable detector 134 is placed opposite the other face on the far side of a material 136 to be gauged. Rotation of shaft 110 under control of motor 112 varies the mean energy of radiation reaching the material 136 as in the preceding embodiment of the invention.

It will thus be apparent to those skilled in the art that with a device of the type disclosed herein it is possible to measure an extremely large range of material characteristics, with a single instrument utilizing only one primary radiation source. In addition to this, the measurements may be made with the instrument or gauge operating under conditions which provide a high degree of accuracy. Both manual and power positioning devices may be used, and servo mechanisms may be utilized to provide an extremely accurate control. The target assembly may assume a variety of shapes, and various types of target motions may be used. Similarly the particular collimating arrangements shown are intended to be illustrative and not restrictive in nature, since other collimating arrangements will be apparent to those skilled in the art.

While the gauge shown herein provides one satisfactory method of utilizing the variable energy absorption spectra producing device of this invention, other gauges may be utilized. A particularly satisfactory alternative gauge is one utilizing a feedback positioning device to adjust the position of the target assembly or carriage to produce a particular level of received radiation flux in the detector. That is to say, the positioning device can be utilized to move the carriage in order to maintain this level of received radiation flux so that the position of the carriage indicates the particular parameter being measured. Other type gauge arrangements may also be utilized without departing from the spirit of this invention.

The invention may be embodied in other specific forms without departing from the spirit or essential characteristics thereof. The present embodiment is therefore to be considered in all respects as illustrative and not restrictive, the scope of the invention being indicated by the appended claims rather than by the foregoing description, and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced therein.

What is claimed and desired to be secured by United States Letters Patent is:

1. A target assembly for varying the mean energy level of radiation emitted by a radioactive source comprising a plurality of bremsstrahlung generators each having a different atomic number.

2. A target assembly for varying the mean energy level of radiation emitted by a radioactive source comprising a plurality of bremsstrahlung generators and a beta collimating section, said bremsstrahlung generators each having a different atomic number.

3. A target assembly for varying the means energy level of radiation emitted by a radioactive source comprising a plurality of bremsstrahlung generators each having a different atomic number, and a beta collimating section of varying width including series of collimating apertures of varying diameter.

4. In a measuring system utilizing a radioactive source for determining the variable absorption characteristics of the material under test, a target assembly for varying the mean energy level of radiation emitted by a radioactive source comprising a plurality of bremsstrahlung generator sections each having a different atomic number, means for restricting the radiation emitted by said source to an area of said assembly less than one of said sections, and means for altering the relative positions of said source and said assembly.

5. In a measuring system utilizing a radioactive source for determining the variable absorption characteristics of the material under test, a target assembly for varying the mean energy level of radiation emitted by said radioactive source comprising a plurality of bremsstrahlung generator sections each having a different atomic number, and a variable beta collimating section; means for restricting the radiation emitted by said source to an area of said assembly less than one of said sections, and means for

altering the relative positions of said source and said assembly.

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United States Patent [19]

DeMent

[11] **3,715,596**

[45] **Feb. 6, 1973**

[54] TELLURIAN OPTOEXPLOSIVE SYSTEM INCLUDING NUCLEAR EXPLOSIVE LIGHT GENERATOR AND TARGET IRRADIATION

[76] Inventor: **Jack DeMent**, 4847 S.E. Division Street, Portland, Oreg. 97206

[22] Filed: **Aug. 7, 1968**

[21] Appl. No.: **750,979**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 407,461, Oct. 29, 1964, Pat. No. 3,414,838.

[52] U.S. Cl. ..... **250/84**, 33/1 HH, 73/35, 240/1 R, 331/94.5, 350/161, 250/83 R

[51] Int. Cl. **G21h 5/03**

[58] Field of Search ..... 331/94.5; 240/1 R; 250/84

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Primary Examiner—Roy Lake
Assistant Examiner—Darwin R. Hostetter

[57] **ABSTRACT**

This disclosure relates to a tellurian(underground) system(an explotron) for the close-in treatment of an irradiable target by explosion-formed electromagnetic energies characterized as reflectable off a frangible reflective optic such that the target is not overwhelmed by non-reflectable explosion energies like blast and plasma. A typical tellurian explotron is a main duct horizontally sited below the ground, within one end of which is positioned and fired a mass of chemical or nuclear explosive (the optoexplosive) that generates electromagnetic and kinetic energies. Junctured midway or at any other convenient site along the main duct is at least one ductoid branch member, which rises to the ground surface and couples with the irradiable target. At the furcation of main duct and branch there is emplaced at a suitable angle a frangible reflective optic such as an aluminum foil mirror which delivers the faster-moving, reflectable radiation via the branch to the target, while the slower-moving, non-reflectable energies transit the main duct and break out the frangible reflective optic, being deposited in the opposite end of the main duct(the shock sink).

25 Claims, 8 Drawing Figures

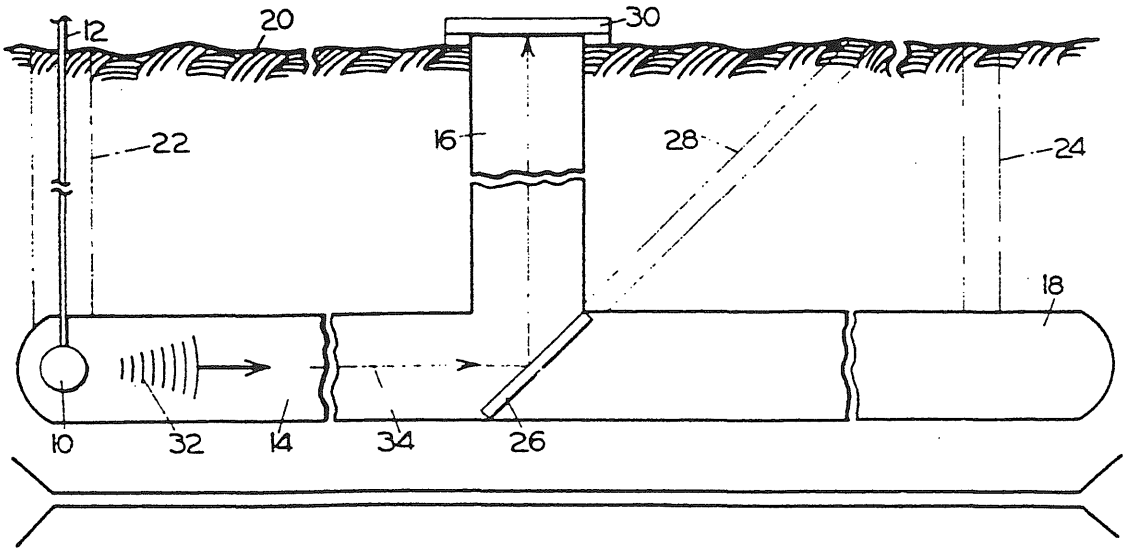
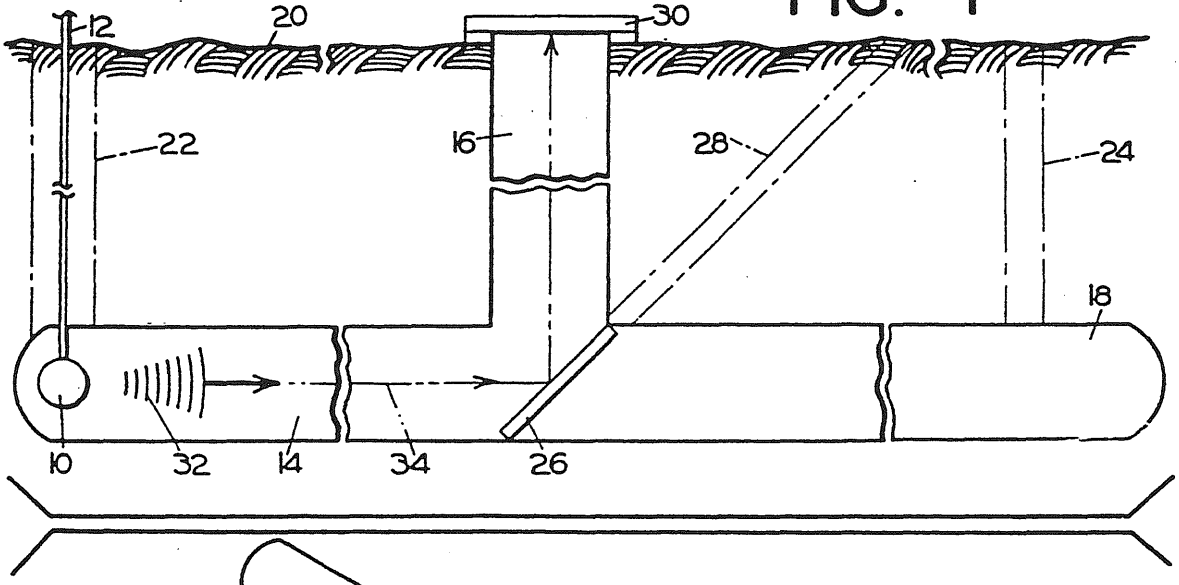


FIG. 1



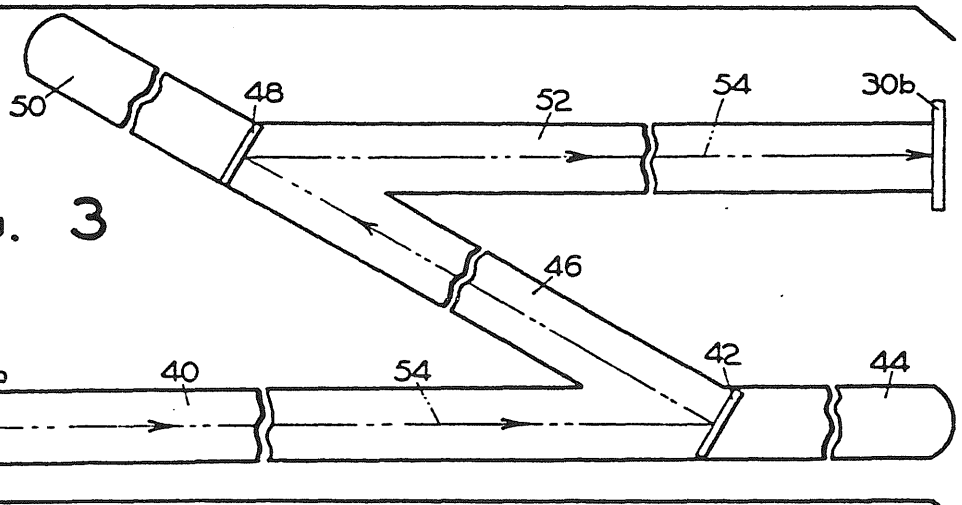


FIG. 3

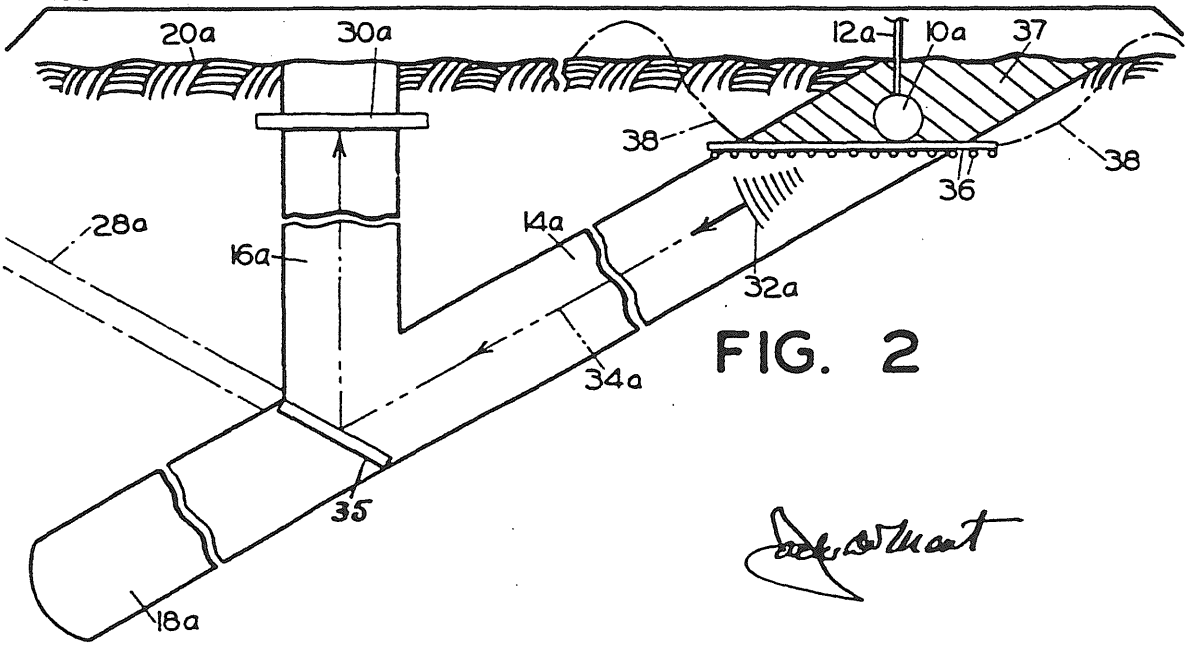
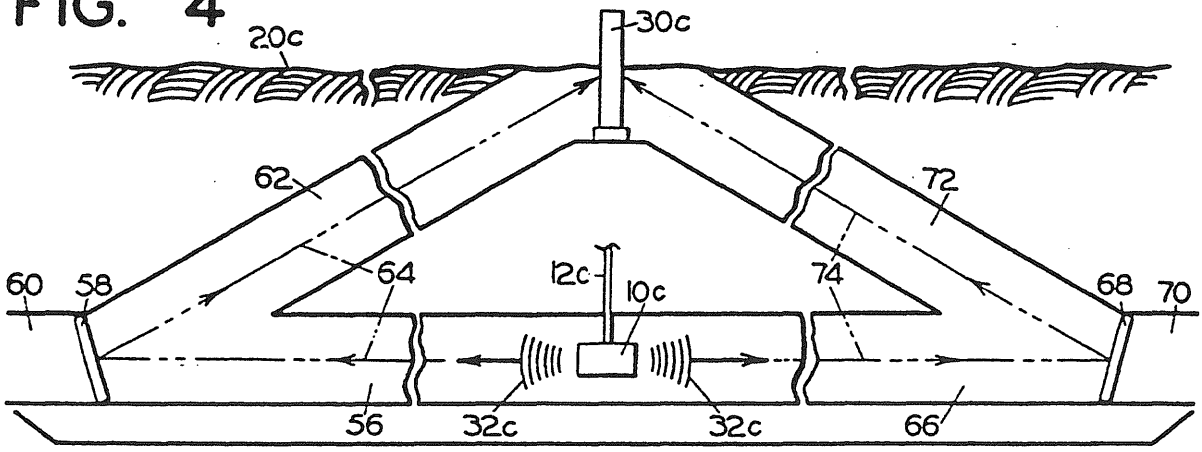


FIG. 2

FIG. 4



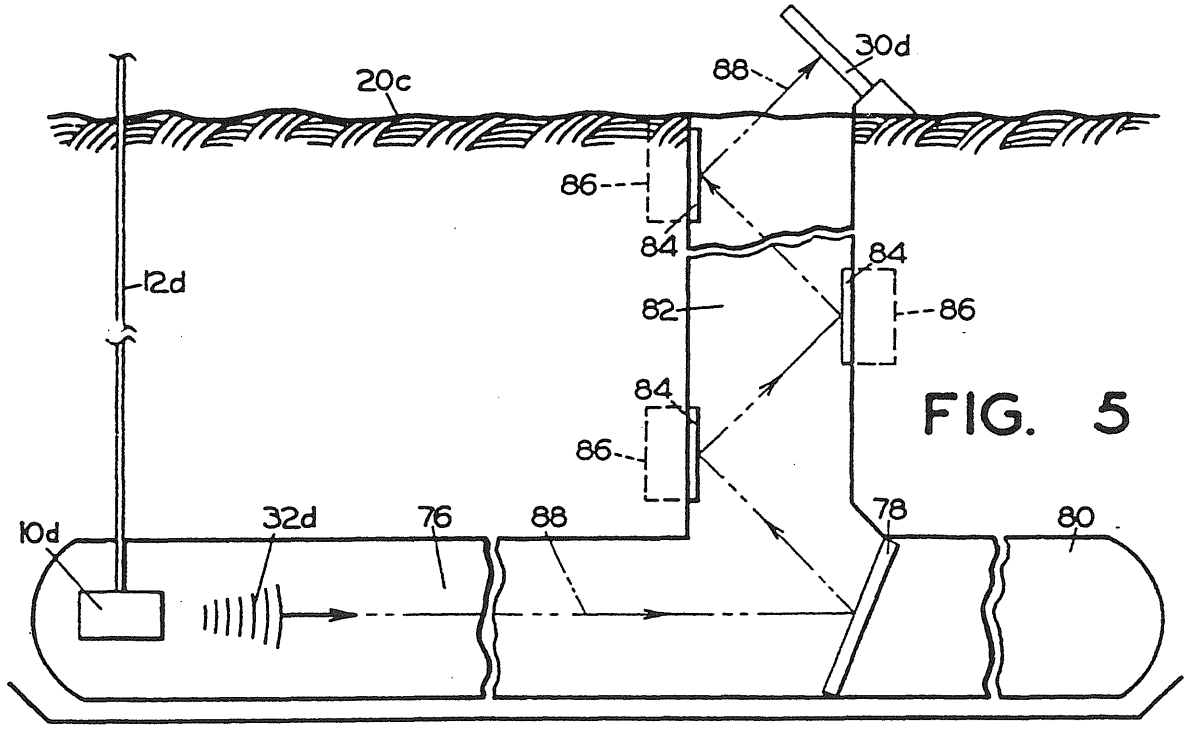


FIG. 5

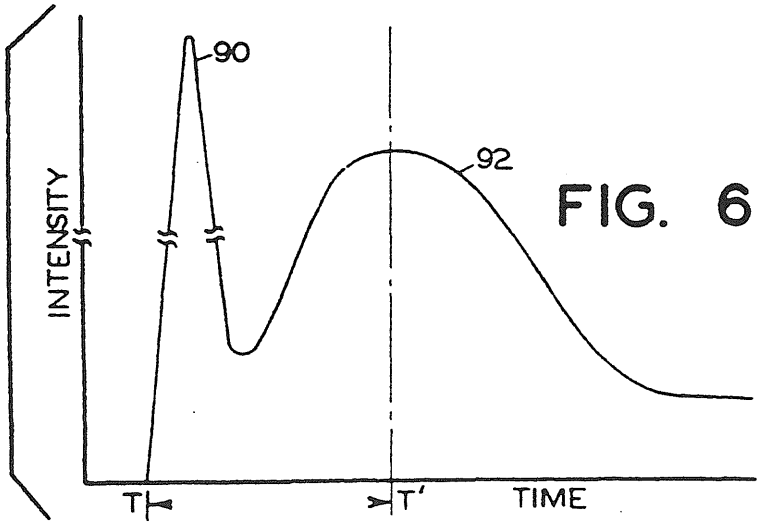


FIG. 6

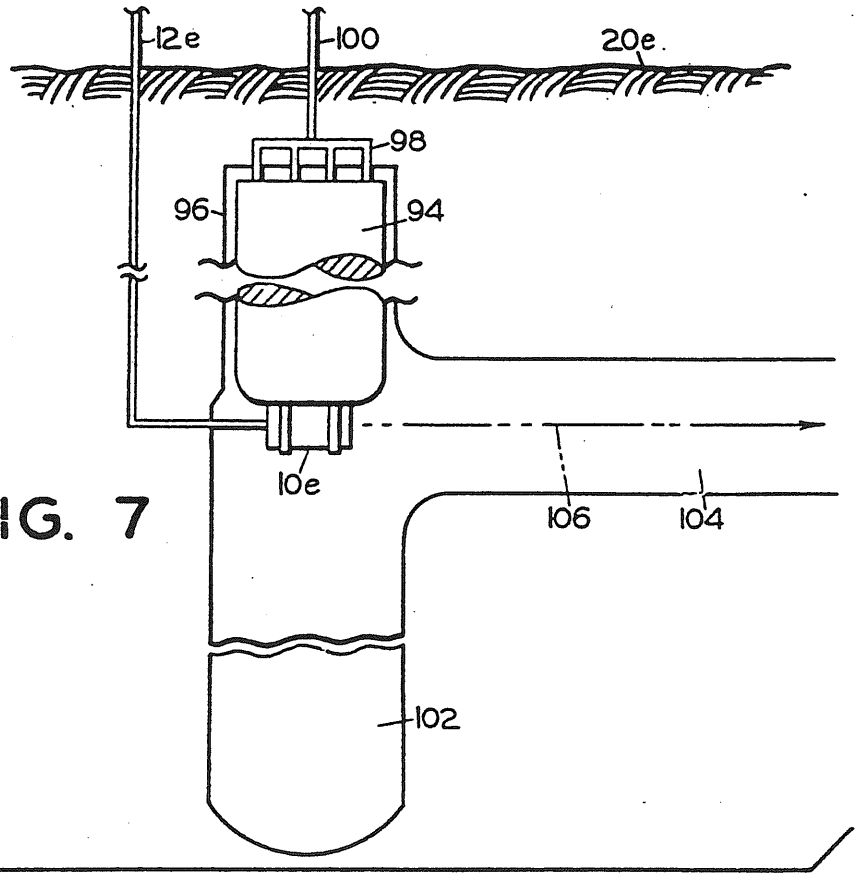

12e
100
20e
98
96
94
10e
106
104
102

FIG. 7

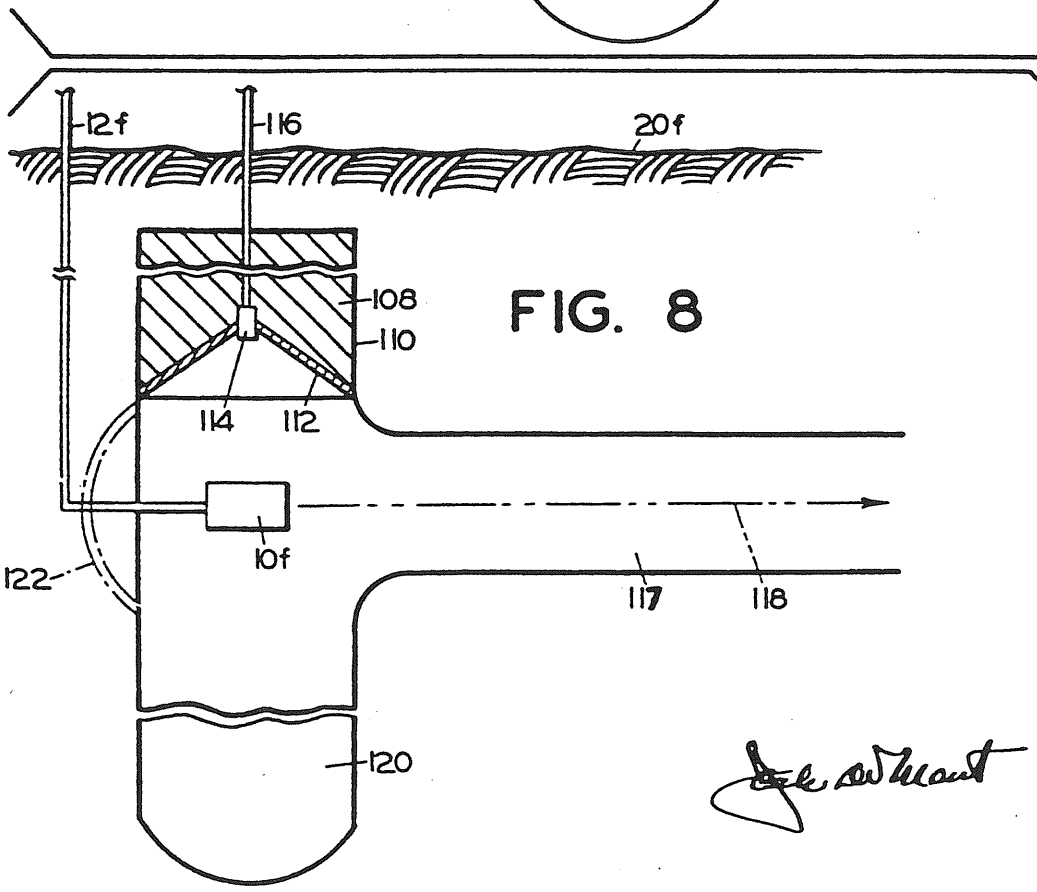

12f
116
20f
108
110
114
112
10f
122
117
118
120

FIG. 8

TELLURIAN OPTOEXPLOSIVE SYSTEM INCLUDING NUCLEAR EXPLOSIVE LIGHT GENERATOR AND TARGET IRRADIATION

This is a continuation-in-part of my U.S. Ser. No. 407,461, filed Oct. 29, 1964, titled "Explodable Light Source and Laser Light Generator", now U.S. Pat. No. 3,414,838, granted Dec. 3, 1968, filed Oct. 29, 1964.

This invention relates to optoexplosive systems, particularly those of the tellurian variety, which employ chemical explosives or explosions(CX) and nuclear explosives or explosions(NX), generally of substantial yield, for the production of certain electromagnetic radiations.

These electromagnetic radiations include those lying in the long wavelength(or so-called soft) X-ray, ultraviolet, visible, infrared, and/or the trans-infrared portions of the spectrum.

The present improvement also includes target irradiation, as well as nuclear explosive light generation. Additionally there is included light pulse generation of sinusoid nature, also a new family of optics—which I designate as frangible reflective optics(FRO).

In addition to the feature of light generation by CX and NX explosions, this improvement is characterized by light (which term will be taken to broadly include the electromagnetic spectrum just delineated, and further explained below) substantially free of blast(or shock), explosion debris, highly penetrating electromagnetic and particulate radiation, and the like, depending upon the explosive employed.

This disclosure includes the following sections:

Objects — Features
Drawings
Geoengineering — Systems Design
Frangible Reflective Optics
Chemical Optoexplosives
Nuclear Optoexplosives
Optoexplosion Modifiers
Beam Manipulation — Large Area Optics
Irradiable Target

In my presentation I have liberally cross-referenced in an endeavor to tie the many facets of this broad subject into a coherent package.

Since this and the parent invention encompass many branches of the arts, sciences and industries—and is a highly multi-disciplinary engineering and systems design entity—it is necessary for me to: (a) explain certain of the relevant facts in the one or more specialties which may otherwise not be clear to those in other specialties, theoretical and/or applied; (b) provide a consistent nomenclature and terminology derived substantially from the various specialties wherever the need may be evident, including the sparse use of acronyms for convenience and brevity, also to point up the novelty of the large family of optoexplosive systems—tellurian or other; and (c) cite and give pertinent, relevant and follow-through literature and sources of information which the artizan, student or other interested party can get a basis in-depth understanding of the phenomena of separation of light from shock in an explosive light source, which information is not always necessary or practicable to set out in lengthy discourse herein.

Herein I employ the term "light" in a generic sense, to include electromagnetic radiation defined as "optical radiation" lying within the "optical spectrum." The

optical spectrum is taken to mean that portion of the electromagnetic spectrum between approximately 10^{-2} and 10^{3} microns. This definition agrees with good physics practice in that the ultraviolet, visible and infrared radiations can be thought of collectively as the optical spectrum not only due to similar emission processes, but also due to common experimental techniques such as the use of lenses and mirrors for focusing the radiation and prisms and gratings for separating the constituent wavelengths, as well as filters, polarizers and like optic elements for imparting some special characteristic to a light beam. The end points of the spectrum are rather arbitrary. On the long wavelength end the infrared and microwaves overlap(hence my use of the term "trans-infrared," supra). The same is true where X-rays and ultraviolet merge, at about 10^{-2} microns(100 Angstroms(A)). Division of the various regions into near, intermediate, far, and extreme, differ somewhat among physicists, and the standard literature is referred to for information of this kind. Depending upon the discipline the wavelengths units may differ, e.g., the micron for the infrared, the millimicron(or nanometer) for the visible, and the Angstrom for the ultraviolet and soft-X-ray. Herein, these units may be used interchangeably.

While I prefer to utilize highly reflective, mirror-like substances of the conventional kinds(e.g., polished metals) in the make-up of an FRO, I particularly point out that when I employ terms like "reflection" and "reflective" I use them in the context of optics, physical optics and like disciplines. Thus: when light(as defined herein) strikes a boundary separating two media(more than two can be involved) of different refractivities, some of the light is specularly reflected, some is scattered or diffusely reflected, and the remainder enters the second medium. The amount specularly reflected depends upon both the angle of incidence, i, and the polarization of the incident light. To the best of my knowledge, for explosive light sources very little factual data are available on polarized explosion light. Unless $\angle\ i = 0$, the reflected light is plane-polarized(partially), even when the incident light is not. The component has its electric vector perpendicular to the plane of i(i.e., polarized in the plane of incidence) and is more strongly reflected than the other. As i increases from 0° to 90° the ratio of the reflectivities of the two components passes through a maximum, called the Brewster angle and given by the relation $\tan \angle i = n$. At the Brewster angle the reflected light is almost completely plane-polarized.

The reflectivity or reflectance, R, is the ratio $R = I_r/I_i$ where I_i and I_r are the intensities of the incident and of the specularly reflected light, respectively. Neglecting absorption and scattering the reflectivity of a transparent medium is

$$R_p = \sin^2(i-r)/\sin^2(i+r)$$

if the incident light is plane-polarized in the plane of i(i.e., electric vector parallel to the reflecting surface); and

$$R_n = \tan^2(i-r)/\tan^2(i+r)$$

if it is plane-polarized normal to the plane of incidence, wherein i is the angle of incidence and r that of refraction.

If the incident light is unpolarized, as appears to be the case of a symmetric or spheroidal explosion of CX or NX, then R should be half the sum of the two foregoing expressions. In the case of an asymmetric, directed-energy or other specialty CX or NX explosion(or explosive light source) it should be expected that R should lie between 0.5 and 1.0.

As the index of refraction of the second medium(the FRO in this case) with reference to the first medium(loading gas or environmental medium in this case) is $n = \sin i/\sin r$, the expressions may be derived to the usual fresnel relation of:

$$\text{If } i = 0,\ R_p = R_s = (n-1)^2/(n+1)^2$$

For purposes of orientation the parent invention sets out the extraction of substantially shock free light from an explosive(or explodable) light source whereby there is fired or detonated an explosive light source characterized as generating electromagnetic energies concurrently with non-electromagnetic energies; directing both of the said energies against a frangible optic; reflecting the said electromagnetic energies from the optic; and shortly thereafter by virtue of the inherent velocity differences between the two forms of energy impacting the non-electromagnetic energies upon the frangible, reflective optic to cause the destruction of the optic; and directing the destructed optic together with the non-electromagnetic energies in a direction away from the direction of the reflected electromagnetic energies.

Typically, the frangible optic includes a breakable or like destructible mirror or mirror-optic, e.g., mirror lens or reflection grating, impacted by energies derived from explosives (e.g., solid chemical explosive, hypergolics, and exploded colloidochemical systems(e.g., metal particulates and gases); also, exploding and imploding wires, sheets, tubes and the like).

There is thus derived a large and flexible family of light sources—which I designate by the term EXPLOTRON—typically made up of a T or Y furcated tubular system wherein the frangible, reflective optic is positioned at the crotch so as to receive explosion-generated light and pass same into one arm of the system while into a shock-sink there is subsequently received non-light energies, i.e., blast and the like.

In this invention I refine and extend certain of the basic features of the parent invention. For example, the frangible, reflective optic can be of timed-life character. Typically this is an optic which fails to reflect incident light at some specific or special point in the explosive light pulse, which point may be well before impingement of the subsequent blast. The result is the reflection of a sinusoid fragment or bit of light from that pulse.

Thus, in the double pulse which characterizes many nuclear explosives all of the light energy of the initial or prompt pulse plus a portion of the longer lasting and usually less intense second or delayed pulse can be extracted by timed-life frangible, reflective optic and shunted into an irradiable target.

Furthermore, the frangible, reflective optic(FRO) can in this improvement be either passive or active. In the case of the usual mirror lens system it is passive; in contrast, when energy is introduced into an FRO to give it special optical qualities it can be said to comprise an active FRO. This an similar features are set out in detail hereinafter, including FRO of both simple(e.g., purely reflective) and compound(e.g., reflection-refraction by virtue of an overlay of refractive or other optically active medium) types.

In addition, herein there is set forth explosive light sources which may be symmetric or asymmetric in terms of light release. For example, CX os mass configuration which upon explosion creates light of cruciform nature and distribution.

It is a feature of the present improvement to utilize fully or partially earth or earth-like conduit arrangements in a furcated mode and having at least one frangible reflective optic to separate and shunt the reflective portion of the electromagnetic spectrum into a light leg, away from and substantially freed of blast/shock energies, explosion debris, penetrating radiation, and the like, the combination of the aforesaid reflective electromagnetic radiations and the unwanted and ancillary energies originating together in the explosion of a chemical explosive(CX), a nuclear explosive(NX), or the combination of the two (CX/NX), as may be desired.

It is a feature of this invention to supply to an irradiable target reflected and reflectable light of electromagnetic nature for purposes of absorption by that target.

It is a feature of this improvement to provide (a) ultrahigh power electromagnetic energy fluxes reflected to an irradiable target and/or (b) specific and special light bands characterized by profiles of large aperture, area or the like.

It is a feature of the present invention to select from an explosion pulse, whether it be CX or NX or the like, a sinusoid fragment of light of particular intensity-time configuration and deliver that sinusoid light bit free of blast and extraneous energies to an irradiable target.

Accordingly:

It is an object of this invention to provide method and means for the separation of light from blast and shock, debris, particulate and penetrating, and like energies generated in a chemical or nuclear explosion or both;

It is also an object of this invention to provide explosive method and means for the production of reflectable X-ray(often called soft X-ray), ultraviolet, visible, infrared and transinfrared light in beams of high energy and/or large cross-sectional area, as may be desired;

It is an object hereof to generate light beams originating in a nuclear explosion which may be characterized as free of nuclear blast and debris and unwanted particulate and penetrating nuclear radiations, which light beams I designate as "clean atomic light"(CAL);

Likewise, to generate CAL beams of shaped cross-sectional profile, which CAL beams I designate herein as "shaped atomic light"(SAL);

It is also an object of this invention to produce intense light beams originating in chemical or nuclear explosion and to irradiate an irradiable target with said beams;

It is an object of this improvement to produce high power light pulses characterized as varying in intensity with time, i.e., the sinusoid bits of optical energy disclosed herein.

Other objects of this invention are set out hereinafter.

Traditionally, explosives have been utilized for their blast and shock effects. In fact, the energy which appears as light flash has often been considered undesirable. Generally this may be said to be true of chemical explosives, and, increasingly true of nuclear explosives. Perhaps an exception would be photoflash bombs which are usually designed for aerial use, but which are characterized by a small amount of blast and a relatively long burning time. Perhaps another exception includes nuclear explosions at reduced atmospheric pressure(at high altitudes), where the optical energy output may attain upwards of 80 percent of the overall yield of the device; for present purposes this will have to be regarded as rather coincidental in that it is an environment-dependent quality and not having to do with the design of the NX per se.

Evidently, then, an entire new science and technology—which I call *optoexplosives technology*—opens once it is feasible to (a) extract blast-free light from a chemical or nuclear explosion and (b) optimize CX and NX to liberate larger proportions of their energies as usable optical energies or light than they presently do. The parent invention as well as the instant disclosure provides method and means for attaining (a). The design optimization of conventional CX and, quite particularly, of certain NX for light generation must be regarded as a rather neglected aspect of the overall energy picture.

Thus, nuclear blast is used, as in PLOWSHARE and like nuclear engineering work; and nuclear radiation is used for food or other product irradiation. But apparently little or no attention has been given the production of blast-free and radiation-free nuclear light by NX, let alone its many actual and potential uses.

DRAWINGS

For other objects and features and for a better understanding of the invention, reference is made to the parent disclosure cited supra and to the following detailed description taken in conjunction with the accompanying drawings which, unless otherwise noted hereinafter, may be taken as diagrammatic, sectional, foreshortened, subgrade elevation:

The drawings in brief:

FIG. 1 is in side elevation an optoexplosive system of tellurian character of T-configuration;

FIG. 2 is in side elevation a tellurian optoexplosive system of Y-configuration;

FIG. 3 is in side elevation a tellurian optoexplosive system corresponding to a multiple Y-configuration or multiple T-configuration, or of other furcation as hereinafter described, and termed a zig-zag or blind-alley configuration for purposes of convenience;

FIG. 4 represents in side elevation a multilegged, tellurian optoexplosive system;

FIG. 5 shows in schematic form and in side elevation a tellurian optoexplosive system of say T-configuration or the like characterized by multiple frangible and/or nonfrangible reflective optics;

FIG. 6 is a graph with arbitrary intensity and time coordinates, which depicts certain salient facets of the energy-shock release of a nuclear explosive;

FIG. 7 schematically represents in side elevation a portion of a typical tellurian optoexplosive system of say T-butt configuration wherein interial(falling, sliding or the like) mass is operant; and

FIG. 8 is similar to FIG. 7, except that a shaped charge or directed or asymmetric explosive force is involved.

Whereas the accompanying drawings generally portray the present invention in terms of (a) side elevation and (b) tellurian (e.g., subterranean) environment, it is noted that the optoexplosive system may be viewed in plan or other appropriate manner as regards spatial arrangement with respect to ground or surface line or contour. Also that the tellurian optoexplosive system can, as desired and according to the modification hereof, be wholly closed or partially closed, i.e., with access and egress in terms of explosive, target, venting or the like. As will be recognized by those skilled in the art and as detailed subsequently, numerous modifications and variations are feasible. The choice of these will naturally depend upon the parameters involved.

Taking the accompanying drawings in detail, with elaboration and modifications subsequently disclosed:

FIG. 1 shows in side elevation a tellurian optoexplosive system characterized by T-configuration. Beneath the surface of the earth(e.g., rock, ice, permafrost or the like) 20, there is a T-shaped tunnel, duct, shaft or like system having three legs 14, 16 and 18. Positioned at or near the end of explosion leg 14 is an explosive device or mass 10, which may be chemical explosive or nuclear explosive or both(CX, NX or CX/NX, respectively), 10 being in communication with firing or detonating cable or the like 12 exiting at 20. Optionally, 14 may have a vent or like duct 22 rising to 20. Optionally, 18 may have a vent or like shaft 24 rising to 20.

Positioned at the juncture or crotch of the T tunnel system, 14, 16, 18, is a frangible, reflective optic 26, which may be a breakable plane or non-plane mirror optic or other frangible, reflective optic(FRO) as hereinafter described. The angular positioning of member 26 is such that it is optically coupled to light passing down 14 and to an irradiable target shown as 30. Thus upon the detonation via 12 and explosion of 10 a prompt burst of light 34 is created, with blast and shock and explosion debris 32 following thereafter, depending upon the nature of 10 and the pressure within the system. Light 34 incidents upon 26 and reflects therefrom to 30. Subsequent blast 32 may destroy the FRO 26, to pass into the shock-sink leg 18.

Further in FIG. 1, FRO 26 may be of such nature that it is characterized by a "timed-life." That is, by virtue of melting, burning, vaporization, explosion, or the like, it ceases to perform as a FRO at a point before the arrival of blast 32, its reflecting lifetime hence deciding the intensity-time qualities of the light pulse reflected into 16. FRO members 26 of a rather large number and wide variety can be employed, and both active and passive FRO members are described later herein.

In FIG. 1 it is noted that the irradiable target 30 is schematically depicted as positioned at the mount of 16 at 20. As may be desired, 30 may be placed in any appropriate position and at any appropriate distance, e.g., mounted upon or within a tower, suspended by balloon, or otherwise positioned in the atmosphere, as long as 30 is optically coupled via 26 to light 34. In the case of explosions of low yield or relatively little destruction to the T system an angular duct 28 can, optionally, be employed to feed subsequent FRO members for a

sequence of explosions; 28 may, as desired, also serve as venting means.

Alternatively, in FIG. 1, light leg 16 together with target 30 need not egress at 20. For example, the entire T system can be subterranean and comprise a closed system, in which case 30 may be positioned within a closed leg 16, say within a chamber or at the end of 16.

FIG. 2 shows in side elevation a tellurian optoexplosive system of Y- or acute angle- configuration, i.e., light arm 16*a* makes an acute angle with respect to 14*a*(the explosion arm of the system), wherein 10*a* is the explosive light source and its ancillary firing means 12*a* positioned in shaft 14*a*. 10*a* is placed at or near the ground surface 20*a*. 10*a* is supported by cradle, support or like means 36, which is destructible upon explosion, and which may be of appropriate material(e.g., metal, wood, plastic) of sheet, coarse screen or mesh or other appropriate structure. As desired, 10*a* can be positioned above the surface 20*a*, as for example in a shot tower. Also, as may be desired, member 36 may be dopant(discussed subsequently) which serves to enhance the optical energy output of the CX or NX 10*a*.

It is seen that FIG. 2 typically depicts a shallow subsurface explosion, a surface explosion or a near-surface explosion, in contrast to the deeper, contained cavity-producing explosion of 10 in FIG. 1. The consequence in FIG. 2 is an explosively-formed crater 38, which follows blast scaling laws known in the art. The fill material 37 is optional, depending upon the modification being utilized. Thus, no fill material 37 may be employed to allow for dissipation of blast energies into the atmosphere(as in the case of CX and so-called clean NX). Or when fill material 37 is employed it may be decouplant substance, as for example heat absorbing material like graphite or ablatives(natural or synthetic, discussed hereinafter), to reduce the the magnitude of seismic signals which may be undesirable for such reasons as target 30*a* jitter. When 37 is employed it need not extend to the ground surface 20*a*, but may be heavily overlaid with rock or the like to minimize surface blow-through of fallout.

Further in FIG. 2, 32*a* and 34*a* represent blast and explosion debris, and reflectable light, respectively. 35 is the frangible, reflective optic aligned to receive 34a and shunt it into the light leg 16*a* and thence to the irradiable target 30*a*. 28*a* is an optional shaft say drifting to the surface 20*a*, after the manner of 28 in FIG. 1. 18*a* is the third leg of the bifurcated tunnel system, comprising the shock-sink into which blast and explosion debris and non-reflectable energies pass.

In FIG. 2 it is preferable in the case of highly brisant CX and high blast-giving NX that the angle between 14*a* and 16*a* be a severely acute one, to lessen escape of secondary shock and to reduce shock diffraction into 16*a*, consistent with choice of appropriate tunnel lengths and appropriately-chosen explosive sizes. The same considerations obtain in minimizing abrupt excursions(positive and/or negative) in pressure, also in the shoot-through to 16*a* of a plasma piston which can occur with over-sized NX charges, which considerations are discussed in some detail hereinafter.

FIG. 3 shows in side elevation or in plan elevation, as may be desired, a closed tellurian optoexplosive system corresponding to a multiple Y-configuration or multiple T-configuration or of other branching or furcation as may be desired, which for purposes of convenience can be designated zig-zag or blind-alley. This system is preferred for high yield, large mass explosions, particularly NX, where multiple FRO passes are desired, and where multiple shock-sinks, 44 and 50 in this instance, are necessary to minimize N-wave pressure variations and plasma piston shoot-through to target 30*b*. Not shown in this schematic diagram are surface-rising drifts which function as vents to compensate for the explosion dynamics just mentioned. Such vents may be of any appropriate number in communication from the ground surface with leg members 40(firing or explosion leg), 44(first shock-sink leg), 46(first light-leg), 50(second shock-sink leg), and 52(second light-leg) carrying the optically-coupled target 30*b*.

In FIG. 3 the CX or NX or the like is detonated via means 12*b* (firing cable), the explosive being 10*b* and of symmetric or asymmetric explosion behavior, within the leg 40, to generate optical radiation of reflectable nature 54 together with the much slower velocity, e.g., several Mach or less, blast and explosion debris 32*b*. Light 54 strikes the first FRO 42 and reflects therefrom into the first light-leg 46 while the blast and debris and the like pass partly or wholly into the shock-sink leg 44; 54 now incidents the second FRO 48 and passes into 52, which is the light-leg or target leg, and thence to the target 30*b* as beam 54 in its second pass, while residual, reflected and/or diffracted blast originating with 10b sinks into leg 50 with the destruction of the FRO 48.

Further in FIG. 3 the angular relationship of the various legs of the system may vary with respect to one another; likewise, the tunnel system may or may not be cut parallel or vertical with the ground surface, as may be desired; thus, the various legs may be set in angular rotation with respect to one another. The target 30*b* may be emplaced within a chamber at the end of leg 52 having an adit for target emplacement and removal.

It is thus apparent that the version shown in FIG. 3 has at least two FRO with corresponding shock-sink legs and light ducts; an appropriate increase in the number of FRO and ancillary legs can be utilized for explosive light production by high yield explosions which incur problems of blast and fireball-derived plasma disposal.

Referring now to FIG. 4. There is shown in side elevation a typical multilegged, tellurian optoexplosive system, which may be closed-loop or open-loop as schematically depicted in the diagram, as desired. In a closed system, e.g., deeply buried, venting adits may or may not be employed. In FIG. 4 10*c* is CX or NX or both, with firing cable or like means 12*c*, positioned in a horizontal shaft, say midway therein, represented by legs 56 and 66. Blast and the like from 10*c* is shown as 32*c*, with the higher velocity light 64 and 74 striking FRO 58 and 68, and shunting into light legs 62 and 72, which converge upon target 30*c*. The shock-sink legs for 56 and 66 are shown as 60 and 70, respectively.

Whereas FIG. 4 shows a two-legged(56,66 and 62,72 and 60,70) explosive light generating system, alternatively one or more legs can be added so as to pipe off blast and light from 10*c* at the level of 56 and 66, to form a juncture therewith at 10*c*, with corresponding shock-sink legs for each additional explosion leg, and with upwardly target-converging light-legs corresponding to 62 and 72, having suitably mounted and aligned

additional FRO means at the Y junction of the tubular arrangement. For example, two additional systems can be 90° each on either side of 56 . . . 66, at 10*c*. This may be said to correspond to a cruciform, spider-legged subterranean structure. In this modification a symmetric explosion-giving explosive can be used or an asymmetric one, e.g., CX which detonates and explodes with the release of light in a cruciform pattern. In the two-legged modification shown in FIG. 4 an asymmetric explosion-producing gun-type NX device can be utilized so as to release its energy more or less linearly in opposite directions, i.e., so that the two stronger explosion energy fields are directed into 56 and 66, respectively.

Further in FIG. 4, as desired and according to the application, the target 30*c* may be mounted within or just at the light exits of 62 and 72, with or without suitable housing. Or the target 30c may be aerial, in which case the angles between 56 and 62, and 66 and 72, are appropriately less acute than shown in FIG. 4. In any event, optical coupling between 10*c* via FRO 58,68 and 30*c* is maintained.

Referring now to FIG. 5, depicted as a T-configuration, and in this respect not unlike FIGS. 1 and 2 insofar as the angular relationships of the three legs are concerned. FIG. 5 shows in side elevation and schematic form a tellurian optoexplosive system characterized by multiple FRO and/or non-FRO situated at say the wall portions of light leg 82.

In FIG. 5 the explosive light source and firing means are 10*d* and 12*d*, respectively. 32*d* and 88 designate blast and explosion debris and the like, and reflectable electromagnetic radiation, respectively. 76 is the firing shaft, with 80 the by-pass shock-sink. 78 is a FR[illegible] aligned to optically couple light 88 with target 30*d* via a series of wall or like mounted FRO members 84, which may be any appropriate number and/or which may comprise reflectable lining, as of polished metal, ceramic reflection optic, or the like, at or subset in the wall of leg 82. 86 refers to optional, secondary shock-sink drifts when the modification of FRO 84 members are utilized. 20*c* refers to the terrain or ground or like surface.

Further in FIG. 5 the target 30*d*, while optically coupled via the FRO means and the explosive light source, may be set subsurface, at the surface(as within a housing), or disposed at a distance, e.g., aerially.

Alternatively, in FIG. 5, one of more means 84 are set before one or more adits corresponding to 86 which are in communication with ground surface or the atmosphere 20*c*. In an optoexplosive system which functions under ambient atmospheric conditions said arrangement serves as vent means to minimize target 30*d* insult by anomalous shock effects, serving to valve and smooth the positive-negative pressure N-wave which may be undesirable when high blast yield CX or NX optoexplosive sources are employed.

It is evident that FIG. 5 may be said to correspond to a hall-of-mirrors or kaleidoscope optical element train characterized by at least one FRO 84 when said train is multiple. The optical train comprising a sequence of optically coupled optic elements of a reflective nature 84 may comprise members either of passive or active properties, or may or may not be selectively or prefrentially reflective, diffracting, polarizing or the like, as desired and as detailed subsequently in this disclosure.

Reflective optics 84 in FIG. 5, or their equivalents when means 84 is rigid(e.g., highly reflective casing, coating or liner for 82) can perform as a flux redistributor. Should spatially non-uniform light flux(as from a spherical FRO) enter 82, then the hall-of-mirrors effect obtains between the focal plane and the sample, the emergent light being uniformly distributed over an area equal to the cross-section of the flux redistributor system comprised of 82 and element(s) 84. The efficiency depends upon the reflectivity of the means 84 or their equivalent(as when rigid, in the form of liner) used at the wall of 82. Arc source thermal imaging systems give about 0.5 transmission by a redistributor of specular-reflecting surfaces.

In properly understanding FIG. 6 a few preliminary words of explanation are in order. Thus: immediately after detonation and during the initial phase of an explosion, whether that explosion be CX or NX, the dynamics of the event are substantially independent of the surrounding environment. Upon rupture of the CX or NX device there may be said to be an interaction with the environment comprising a feedback of explosion behavior. For example, an explosion in air at atmospheric pressure involves the interaction of mechanical(e.g., blast/shock) and optical(light) energies. When this atmosphere is absent this interaction, especially that of shock formation which, by definition, involves formation of pressure waves(characterized by pressure-time and velocity parameters), is reduced to a point approaching zero (e.g., in an absolute vacuum the ideal situation would be the complete absence of shock because of the lack of pressurable media by which that shock is formed and transmitted; the ideal situation is never attained for large explosive masses because of explosion debris; pragmatically the situation is closely approached by properly designing-out media which favor blast and shock formation, as will be indicated subsequently).

Whereas the blast/light energies from CX(in the atmosphere or like media) or NX(under anatmospherically provided conditions, e.g., at high altitudes or within evacuated enclosures) may be simplistically stated as essentially a curve of rise-time, peak of variable plateau, and fall-time, for each of the two kinds of energies, the situation characteristic of NX is more complex for gas environments. The latter is developed in FIG. 6.

Further in FIG. 6: Fourier analysis lays the basis for the extraction of a sinusoid(bit or fragment, as herein designated) from from a larger or more complex light pulse. Illustratively, the sinusoid light bit is plucked from the explosion light monopulse or multipulse(bipulse form as depicted in FIG. 6) by a timed-life FRO. By definition a timed-life FRO ceases to perform as a reflective optic at a point in time up to and including shock-impaction upon the FRO. The case of blast-destroyed FRO is set out in the parent disclosure; shock-generated light behind the shock front may or may not have time to undergo the necessary optical transition before FRO failure by mechanical insult or the conversion to destructive thermal energy by blast, depending upon such factors as absorbance, rupture strength or yield point, spallation and like properties of the FRO and the shock flux together with Mach value.

FIG. 6 represents the timed-life of a FRO of life T - - - T', with T the start of the life of that FRO. T' and the dashed vertical coordinate at the centrum of the second optical pulse 92 depict the end of the life of the FRO, i.e., the fail-point of the FRO(i.e., failure due to thermal shattering, fusion, vaporization, pyrolysis or burning, sublimation, or the like (note is made of the fact that these and like qualities inherent in the FRO performance are duly set forth in the parent disclosure)). In other words, the T - - - T' value and the linearity or non-linearity of FRO response, particularly as T' is approached and more energy is deposited within the FRO, is essentially decided by the thermophysical properties of that member.

FIG. 6 graphs on arbitrary intensity and time coordinates optical(electromagnetic radiation) output vs. time. This graph, called a double-pulse graph in nuclear explosion phenomenalogy, has its coordinates decided by, among other things, the nature of the NX source and the environmental medium, e.g., air at atmospheric or near-atmospheric pressures. As just indicated, the double-pulse graph tends to coalesce into a single pulse depiction as environmental pressure is reduced. Since nuclear explosions in gasified media other than air, e.g., the so-called inert-gases(e.g., He, Ne, Ar), chemically-reactive gases(e.g., H_2, nitrogen oxides(of which there are seven potentially available), C—H gases of the aliphatic series of single, double and triple bonding), also inorganic and organic vapors(e.g., water, D_2O, T_2O, Hg, halogens, polycyclic hydrocarbons) are scantly or fully unknown it is necessary for purposes of development of this facet of the present invention to rely upon FIG. 6 graph.

In FIG. 6 there is shown an initial, prompt pulse of electromagnetic radiation 90 created by an NX within the atmosphere or the like, with subsequent drop due to the start of a slower NX device-created fireball or second-pulse 92 characterized as relatively less intense and of greater duration.

Further in FIG. 6 T - - - T' illustratively depicts the pick-off of sinusoid light bits ranging downward from the coupling of blast with the FRO. Thus: the vertical dashed line of T' can represent the arrival of the shock energy, in which instance the FRO is said to be mechanically destroyed(directed or indirectly, as just indicated), or, below this point in time, for example, only the prompt pulse 90 may be reflected; or, only the leading edge to centrum of 90 may be reflected; or, T' may be set out on the trailing edge of 92 so that the mass of hot gases in the region behind the radiation front, the isothermal sphere of the NX-type explosive light source, is advantageously utilized; or, the like.

The large family of variegated timed-life FRO means is discussed in more detail hereinafter. At this point suffice to state that an FRO can be designed to fail, i.e., possess a definite lifetime, because of its passive thermophysical nature, but also because of active, non-CX or non-NX destruct-energy inputs. For example, the FRO can comprise high detonation rate or velocity(e.g., say of the order of 8000 meters/sec) chemical explosive, so as to exhibit self-destruct-upon-command(as by electric firing).

From FIG. 6 it is thus evident that an object and feature of this invention is an explosive light source which need not rely upon light-trailing shock or blast to chop off light reflection of a FRO.

Referring to FIG. 7 there is shown in side elevation a subterranean 20*e*, portion of a typical tellurian optoexplosive system of say T-butt configuration wherein inertial or gravity (falling, semi-implled fall, sliding or the like) is operant upon a piston member 94. In FIG. 7 the T-butt portion is formed as secondary extensions conjoining the explosion leg or chamber 104, as described in previous drawings. In apposition to(to form the arms of a T) 104, at say 90° or other appropriate angle, and forming secondary or branching legs are upper and lower drifts 96 and 102, respectively. An inertial load or gravity piston of freely fallable or slidable nature, 94, is suspended within 96 by lug, cable, beam or like means 98. Movable piston 94 is characterized as explosively detachable or impelled by explosive means carried in 98. Thus 98 preferably includes electroexplosive devices, EED's, as for example a series of explosive lugs, bolts or guillotines. A suitable firing cable 100 circuits 98. Optionally, means 98 may carry a bursting charge which serves to assure detachment of 94 and provide an initial impelling force.

Mounted say on the face of 94 is CX or NX 10*e* with its firing means 12*e*. 10*e* is so positioned that preferably upon the initial phase of explosion it sends light 106 through leg 104 to the FRO.

Depending upon the explosion dynamics of CX or NX 10*e*, and say substantially at the time of firing of 10e(or shortly before or shortly thereafter, depending upon the parameters involved, e.g., the mass and fall rate of 94, and the relative positioning of 10*e* and 94, as well as the length of shaft 96, and the like, as will be recognized by those skilled in the art) means 100 is fired to explode 98 and release 94. Member 94 falls into sump, pit, tubular vault or the like leg 102, tamping or valving off within 102 the partly developed explosion of 10*e*, in essence catching the explosion at a point in its formative stage and diverting the developing and immature explosion away from an FRO optical coupling arrangement.

Typically in FIG. 7 the piston 94 falls freely once detached from means 98 into leg 102, as when a 90° angularity of involved between 104, 96 and 102; or, 94 can be adapted to slide from 96 into 102 when the two said legs are shafted at angles off 90°, as may be desired. Concurrently 94 should maintain structural integrity until it enters and plugs 102, at which time the residuum of the explosion of 10*e* becomes a contained or semi-contained explosion.

Further in FIG. 7 94 is typically a cylindrical mass, as for example a cylindrical container of high strength steel or refractory ceramic having a face of explosion-resistant quality and say interiorly strutted construction to maintain geometric integrity during its force history. Such a piston container is expediently loaded after placement with high density material, e.g., lead or other heavy metals, rock, or a combination of the two. Alternatively, dense core material of diameter less than 96 may be employed. Optionally, a semiprotective sandwich of substance of high thermal energy absorption and low thermal energy conductivity may be emplaced between 10*e* and the face of 94, as for example a decouplant or inorganic ablative.

Whereas in FIG. 7 the CX or NX 10*e* may be mounted on the face or bottom of 94, an alternate ensemble is the positioning of 10*e* on the back wall of the

T-configuration(96 . . . 102) in line with the axis of 104, with 94 set at a distance within 96 above 10*e*. This arrangement may be preferred when T - - - T' sinusoid fragments(cf. FIG. 6) are desired when, say, 10*e*, is low order detonation or when the environment is anatmospheric. In terms of explosion behavior 10e may be symmetric or asymmetric, as may be desired, as for example in the latter instance to minimize burst force which opposes the fall of 94, as well as to optimize light input 106 into tunnel leg 104.

Commensurate with good mining engineering practice as applied to the present invention drifts 96 and 102 in FIG. 7 (the same obtains for FIG. 8, below) should have substantially smooth walls. The walls can be lapped to remove irregularities and surface projections, flame-sprayed ceramic coating in whole or in part, provided with cemented metal, metal carbide, metal nitride or ceramic tile in tubular lining form, metal or graphite bar slideays, or the like. Moreover, the face of member 94 may be other than plane with rounded or champfered edges, as for example 94 may have a conical nose(which may or may not be truncated) after the fashion of projectile or missile shaping, with or without heat-shielding media known in the art.

Those skilled in the art will readily recognize that the modification shown in FIG. 7 is more suited for relatively small yield 10*e* energy sources characterized as of low brisancy and low detonation rates with the consequently slower developing fireball (as in NX) or flashbody(as in CX).

In FIG. 8 there is set out in side elevation the subterranean 20*f* elbow-butt end modification of the explosion leg 117. In opposition at say 90° or other appropriate angle and conjoining 117 are secondary legs or drifts 110 and 120. Emplaced say at the crotch of 110, 120 and 117 and axially with 117 to provide light energy 118(which couples with the FRO) is CX or NX source 10*f* and its ancillary firing umbilical 12f.

As desired, the back wall delineated by 110 and 120 may comprise a concavity 122. For example, 122 may have a radius of curvature such that should it be a mirror lens the focal point coincides with the FRO placed on down in 117; or, the energy cone generated by 122 may truncate with an area approximating the area of the FRO. 122, in such a modification, may be lined with reflective, temperature-resistent ceramic (e.g., anatase or MgO based material); or, the lining of 122 may be of metal which upon CX or NX radiant energy deposition behaves as a dopant to enhance light generation.

Further in FIG. 8 there is positioned in leg or chamber 110 an asymmetric explosive charge 108. This may be a directed-energy cylindrical CX of high brisancy or, preferably, a shaped or hollow charge(also variously known as Munroe, Neumann, and Stettbacher explosive charges, depending upon the variant—of which there are many known in the CX art in particular).

As schematically shown in FIG. 8 the asymmetric or shaped charge ensemble includes say a cylindrical mass of bursting CX 108 having a conical or like face concavity usually provided with a metal, glass, ceramic or other liner 112. At the apex of the cone (or set out therefrom by support-extension means, as desired) there may be a primer-detonator 114 in axial flash-tube communication with the seat of the charge 108 which, in turn, carries a detonator-booster (not shown) in circuit with a suitable firing line 116. Optionally, member 114 may be thermally sensitive so as to be detonated by the radiant flash of 10*f*, with or without explosive delay element, eliminating the need for 116 and the synchronization which may be required with the firing of 10*f*, as explained for FIG. 7. Simpler as well as more sophisticated shaped charge ensembles are well known in the explosives art and need not be detailed at this point.

Further in FIG. 8, upon firing 10f with the simultaneous or time-lapse actuation of 108 there issues from 108 an explosive jet of exceedingly high velocity and force. This acts in the manner of a plasmoid piston first to constrain and then to force the explosion developing out of 10f into vault 120. The interception and cut-off is decided by the hollow charge explosion velocity and pressure, through time, relative to the opposing explosive forces of the CX or NX 10*f*.

The interaction of the two aforementioned explosions and the blocking and displacement of the 10f explosion in a portion of its formative stages by the more powerful directed-energy explosion of 108 poses problems for solution of rather formidable mathematical complexity. These appear to be reducible by computer using hydrodynamic analogy and similitude. Otherwise, in the simpler optoexplosive systems, e.g., the smaller versions of non-NX variety, empirical or modeling approaches can be utilized to advantage.

GEOENGINEERING — SYSTEMS DESIGN

The tellurian medium(e.g., 20, 20*a*, and 20*c* in FIGS. 1, 2 and 4) may be of any appropriate solid. For example, alluvium, tuff, tuff/alluvium, granite, dolomite, rock salt, basalt or other igneous, metamorphic and sedimentary rock or combinations thereof, porose, vesicular or not. The tunnel system may be disposed such that one or more of its legs intersect a stratum, fault or geocline, such that two or more rock types or geologic formations are included for purposes of seismic refraction away from the target and/or FRO; or for density choice so as to enhance lithostatic pressure (or the converse, to provide elastic dissipation of explosion energy); or for reasons of economy and ease of engineering operations.

Included as tellurian media are such miscellaneous environments as those comprising coal and coaliferous rock, ice and highly compacted snow, and permafrost. The latter are of especial interest in connection with optoexplosive light generators which must be remotely located because of high yield explosive sources. Glacial, berg or other high density ice and permafrost are of interest from a workability standpoint, also because of optical properties(e.g., the increased reflectivity of smooth ice on shaft walls). Thus, steam-smoothed ice may have optical dopant characteristics when frozen-in situ slurries of water and metal or other dopant admixtures have been applied to the wall surface.

Coal, on the other hand, behaves as a thermal energy absorbent and a decouplant, as in an explosion chamber sculpted out of a thick coal seam. Likewise, vent drifts rising to the surface and passing through coal perform in a similar manner, serving to take up the energy of and therefore contribute to the degeneration of explosion plasma.

The systems engineering of an optoexplosive generator, especially that disposing to large yield CX and NX light sources, is particularly attractive in the case of tellurian media including frozen water. Permafrost may be taken as an example of such a medium: R.J.E. Brown(The Polar Record, 13(87), 741-751(1967)) details information about perennially frozen ground. Canada and the USSR together possess most of the territory in the Northern Hemisphere underlain by permafrost. Permafrost varies in thickness from a few centimeters at the southern limit to several hundred meters at the boundary of the continuous zone, which is approximately 60 to 100 meters in Canada and 250 to 300 meters in Siberia.

Unfrozen layers—called taliks—are of interest in the systems design of an optoexplosive light generator. Taliks may occur between layers of permafrost and, therefore, from the standpoint of mining engineering workability(tunneling, shafting, or the like) are of considerable potential service-ability. The depth to the permafrost table is widely variable, ranging between about 0.5 and several meters. The active layer, which freezes in winter and thaws in summer, does not always extend to the permafrost table.

In the continuous zone, permafrost occurs everywhere beneath the ground surface(e.g., 20*c* in FIG. 4, and 20*c* in FIG. 5, and so forth in the accompanying drawings). In Canada it varies from about 60 to 100 meters in the southern zone, to thicknesses between approximately 400 to 500 meters in the Arctic. There are numerous permafrost features, and in addition to taliks mention should be made of thermokarst associated with the melting of ground ice. Certain of the near-polar Arctic and Antarctic areas exhibit exploitable peculiarities involving the change-of-state of water(i.e., to-and-fro of solid and liquid water).

This is a subject, like that of mining and mining engineering, of long history and extensive documentation. Reference is made to: Marie Tremaine(ed.), "Arctic Bibliography", Arctic Institute of North America, volumes 1 to 7, Washington, D.C., U.S. Government Printing Office, 1953-1957, which seven volumes comprise an alphabetical arrangement by author of 43,464 titles, annotated; also, to V.J. Creasi, "Arctic Bibliography", U.S. Weather Bureau, Washington, D.C., 61 pp., CFSTI(AD 666,594)1968.

From the standpoint of geophysical modeling, thermodynamic treatment, and physicochemical characteristics, I would here point to permafrost as rather a unique medium. Simplistically, it can be viewed as a heterogeneous solid composed of a solid (earth) and a solified liquid(ice), the behaviors of each component as well as the composite being different for different kinetic and electromagnetic input energies. The ice, being vaporizable, acts to take up transfer-energy communicated to it by the more absorptive solid component while, at the same time, may be considered to have the qualities of a decouplant. Concurrently, of course, iced surfaces of shaft and tunnel walls behave as reflecting agents. Depending upon the density of the permafrost and the solid:ice ratio, and taking into consideration sorptivity(as from voids or structural breaks), this tellurian medium should behave to absorb explosion debris and radioactive particulates.

The making of holes for an optoexplosive system is made by any of the conventional tools and techniques, consistent with economic factors. There are four general drilling methods which can be used for boring holes up to 8 feet in diameter: (a) churn drilling, (b) auger drilling, (c) core drilling, and (d) rotary drilling. These not be described in detail here, for they are well known in the art, but suffice to say that by means of rotary drilling holes over 5 feet in diameter to depths of upwards of 3000 feet can be made. As dictated by the medium the hole may or may not be cased. Calyx or large bore core drilling enables hole making in larger diameters, usually with the recovery of a consolidated core. Properly trimmed and cased(and/or faced, as previously described) such a core can be employed as member 94 in FIG. 7, as desired.

Means other than drilling can be used for tunneling at angles abruptly off the vertical. Hard rock nd coal mining techniques using explosives, for example, as well as aquifer and railroad tunnel methods, can be taken advantage of. These essentially non-drilling means are utilized in instances where a shaft of other than circular section is desired.

Full or partial casing of the tunnels may or may not be used, consistent with geologic considerations and the performance desired from the optoexplosive system. Timbering and posting and their equivalents, in accordance with usual mining methods used for lode formations having caving tendencies, can be employed.

Multiply timbered, strutted, posted or equivalent members within a tunnel(e.g., 14 in FIG. 1; 14*a* in FIG. 2; 40, 46 and/or 52 in FIG. 3; 56 and 66, and/or 62 and/or 72 in FIG. 4; 76 and/or 82 in FIG. 5) are of interest in this invention with respect to the reduction or diversion away from a target of anomalous, secondary, diffracted shock and blast, i.e., utilization of tunnel cross-member equivalents, for CX and mathematical modeling test are reported in the literature available to the artizan (OPERATION DISTANT PLAIN). Evidently, however, the optical parameters of interest in this invention were not monitored in the DISTANT PLAIN series.

The tunnels, shafts, adits, boreholes, ducts, and the like conduit members variously and interchangeably designated herein in accordance with common naming practices, i.e., the one or more of the legs forming the furcated light-blast shunting system hereof, may be conveniently classed as (a) natural and (b) man-made.

The man-made chambers and conduits are the preferred of the two classes, for obvious reasons. However, I point out that for reasons of economy, feasibility workup and prototype testing, and remoteness, and the like, that certain natural cavernous and conduitiferous structures can be advantageously employed. For example, natural caves to provide the shot vault and explosion leg member 14 of FIG. 1, say suitably engineered at or near its orifice to permit the boring of, or construction of, the necessary other legs 16 and 18, leg 16 of which in FIG. 1 may of course correspond to the housed or unhoused target 30 set out at or above the ground surface 20, with a suitable tricoupled FRO 26. Of interest for low order detonation optoexplosive sources, in this connection, is also the use of the naturally formed arched rock or ice structure, as may be desired.

Illustratively, I prefer a tubate, furcated system, (b) supra, comprising at suitable burial depth at least an explosion chamber and explosion leg of any convenient or appropriate attitude with respect to surface terrain. The walls of the tubate system may be partially or wholly: (a) trimmed, lapped, smoothed or the like; (b) cased or lined; and/or (c) provided with wall projecting means characterized as not reducing the optical energy flow below a usable value but, concurrently, operant as say anechoic analogs("anablastic means") which serve to reflect and diffract blast and plasma back into the leg of origin, i.e., away from the direction of the FRO, or at least set up turbulence and eddying of the non-optical forms of energy. Means (C) is designed in accordance with fluid, blast and like mechanics, which aspect of the subject need not be detailed here.

Cased or lined shafts, (b) supra, serve in the usual mechanical reinforcing capacity to prevent cave-in; to reflect light when polished or possessing reflective characteristics; to ablate when it is desired to reduce temperature(more feasible in small CX powered systems) and perhaps at the same time to assist in the degeneration of flame or plasma; to behave as an incandescent or color temperature-increasing optical dopant; and the like. Shaft liners and wall projecting means can be employed cooperantly.

Importantly, shafts which are cased, lined, walled, coated or otherwise sealed function to:

a. maintain reduced pressure within part or all of the system;
b. maintain increased pressure within part or all of the system;
c. maintain a bottling integrity when part or all of the system is loaded with gas other than air at say atmospheric pressure.

Situations (a) and (b), supra, for example, may involve pressure differentials among the various legs, with frangible or rupturable sealing membranes or diaphgrams to assure compartmentalization. These are of suitable materials, physically and optically. The atmosphere within a system may be air, pressurized air, tenuous air, or, say the so-called inert gases(e.g., He, Ar, Ne, Kr), as well as nitrogen, nitrogen oxides, hydrogen or other gaseous media, not excluding the vapors of inorganic, metal-organic and organic substances chosen because of physicochemical and spectral properties.

Sealed shafts and tunnels are also desirable when the rock or other tellurian medium contains water, the steam from which in the absence of venting or like measures may insult the target and instrumentation which may be placed therein.

It is established that NX energy conversion to optical energy with concurrent reduction in shock and blast increases with decreasing pressure. For example, when the pressure of the environmental atmosphere of an NX is taken down to about 9 mm Hg the optical energy output approaches 0.8. Thus in FIG. 6 the bipulse, 90 and 92, of an NX source would tend to coalesce into a monopulse as the pressure is reduced. The consequence, as depicted in FIG. 6, is that the integrated NX output energy is enhanced, and the 30 milliseconds value for a 1 KT NX for T - - - T' is time-extended, i.e., T' has an apparent value more towards the trailing edge of 92.

The cross-sectional profile of the shafts, tunnels and the like is usually circular(as when drilled). However, these may be arched, ovoid, polygonal(square, rectangular, triangular, and so forth), as may be desired. The face or aperture of the various legs may differ from one another. The side-elevation profile, likewise, may vary greatly, as has been described hereinbefore, and as is set out subsequently as regards pressure, plasma and like control.

The cross-sectional profile of the light leg, e.g., 16 of FIG. 1, is important for the production of what I term a shaped light beam. In the special case of nuclear explosive-derived light I employ the term "shaped atomic light"(SAL).

As generally defined here a shaped optical beam or a SAL is a beam of light characterized by a face contour matching or adapted to match optimum light energy injection into a target. Should the target be rectangular, then the beam is shaped rectangular; should the target be ovoid, then the beam is shaped ovoid; should the target be of irregular profile, then the beam is shaped to a corresponding irregular profile. While this is somewhat of a simplified approach to the subject, it nonetheless serves to point up beam-target matching, other things being equal; also, target irradiation where only a part of the target is to be exposed. By use of the expression "-simplified approach" I do not take into consideration such parameters as the inverse square law, target distance, and the like, all of which obviously enter the picture.

In addition to shaping the exit portal of the light leg, e.g., 82 in FIG. 5, and 62 and 72 in FIG. 4, a light-shaping member or aperture stop(or contrastop) of any necessary or desired opening configuration can also be used, which modification is preferable for a sequence of changes. Such a member may be a suitably thick and strong slab of refractory rock, metal or ceramic.

The cross-sectional or face area(throat or aperture, as variously termed by the different disciplines involved) of the various legs, particularly the light leg(e.g., 16 in FIG. 1 and 16a in FIG. 2), may range from several square feet to several hundred square feet, or more(cf. the discussion given subsequently of venturi, and converging and diverging "nozzle" (especially light leg geometries). This is usually decided by the size, type and configuration of the optoexplosive system taken together with the kind and yield of explosive light source.

An abandoned railroad tunnel, of which there are several hundred in the United States, has a face area of upwards of 150 to 180 square feet. The thousands of abandoned or worked-out lode or other hard rock mine tunnels and shafts range in face area anywhere between about 25 and 100 square feet. These are examples of ready-made tellurian system components which, in addition to their usual remoteness and virtual lack of cost, can be utilized for experimental, feasibility and prototype testing.

Likewise, extant in the Montana-Nebraska area are some 150 abandoned missile silos which measure 80 feet in depth and have a face area of approximately 125 to 150 square feet. Missile silos and vertical mine shafts are adapted to a simplistic modification of this invention. Namely, they comprise the light of explosion leg loaded at or near the bottom with a large mass of slow-

firing, low-order detonating optoexplosive composition.

At the surface exit of such a tunnel there is positioned the FRO at an appropriate optical coupling angle, say 45°, so as to direct reflected light to a target housed an appropriate distance away on the surface of the ground. The FRO may be mounted in a short-leg tower or emplaced by other suitable structure. While this basic form of the invention is not depicted in the drawings, I do not exclude it from the scope of the present invention. One advantage of this modification, as will be readily appreciated by those in the art, is that complex venting(of gas and plasma) means are not required, for there may be a plasma piston/shoothrough and a subsequent absorption by the atmospheric overburden without target insult. Such an optoexplosive system is well adapted for CX powered explosive sources, less so for NX because of release of radioactive debris.

The explosion or firing portion of the leg(e.g., means 10 in leg 14 of FIG. 1) may be enlarged into a suitably sized room or vault. Decoupling may or may not be employed, as desired. The crotch or conjoined leg portion(e.g., at 26 in FIG. 1) may be enlarged into an FRO chamber which is square, rectangular, spheroid or bulbous, or of other convenient volume geometry—particularly when FRO means of special sizes and contours are used.

Furthermore, none of the legs of the optoexplosive clean light generating system need be of the diameter, face area, or sectional geometry as the other legs. Thus it may be desirable in the case of high yield(brisant or blast-wise) explosions to have a light leg, e.g., 16*a* in FIG. 2, but a few tenths the face area of either 14*a* or 18*a* of FIG. 2. This, among other things, is to allow for the very rapid fluid pressure differentials which may develop. This facet of the subject is detailed hereinafter.

The length of the legs of the furcated system is varied according to CX or NX yield and the design of the system. Usually the system will have a light leg(e.g., 82 in FIG. 5, and properly overburden-compensated to provide lithstatic constraint 62 and 72 of FIG. 4, and so forth) at the least the burial depth of the explosive light source in the case of a T-configuration(as in the cases of FIG. 1 and FIG. 5), and greater should the light leg(s) join into the FRO crotch at a non-90° angle(as in the cases of FIG. 3, FIG. 2, also FIG. 4). In the more complexly tunneled and shafted systems the lengths are accordingly greater. Likewise, in the interrupted optical explosion versions like FIG. 7 and FIG. 8, the leg lengths can be foreshortened, particularly when there is a deep sump(e.g., 102 in FIG. 7, and 120 in FIG. 8).

For NX light generators the minimum leg lengths can be approximated on the basis of information extant on the damage to mine workings. Thus: a 1 KT NX shot in granitic rock causes only minor damage and offset at approximately 400 feet; a 2 KT at about 600 feet; a 5 KT at about 1000 feet; and a 20 KT at about 2000 feet. I believe that the confidence level decreases with yield, so a safety factor should be built into the design.

The RAINIER shot(1.7 KT) conducted at about 900 foot burial, and certain other NX underground shots since September of 1957 are frequently employed to get data for scaling laws. Since in the present improvement NX light generating sources utilizes, generally speaking, yields below say approximately 0.5×10^2 KT, and especially below the hectoton(hT) and dekaton(daT)—down to 1–2 tons(of particular interest when doped to enhance light output), it should be mentioned that extrapolations on large yield NX bursts cannot be made with confidence on the basis of present knowledge.

For example, the physical properties of the rock have little, if any, effect on the size of the cavity produced. The limiting parameters are device yield, the gas-producing constituents of the rock such as water, the depth at which the device is exploded, the average density of the overburden and the concomitant lithostatic pressure, venting and decoupling, and the like. However, for purposes of elucidation and for those in the art the following is of interest as it may apply to this facet of the present invention.

First, the equations of state of geologic materials are of fundamental importance in determining response to high yield explosions, particularly NX explosions. The equations of state derive from geophysical and laboratory measurements of physicochemical properties, also from theoretical calculations of the high pressure and high temperature conditions otherwise not feasible for measurement. Physical measurements of ground motion generated by explosions are used together with equations of state, chemical and thermodynamic theory, and the laws of continuum mechanics are employed to develop mathematical models for the prediction of explosion phenomena.

Nuclear engineering and excavation information like that growing out of Project PLOWSHARE experiments very largely appears to fall into two classes: (a) contained underground explosions, and (b) cratering. Scaling laws for both of these are available. In the case of (b), cratering, the interest would be secondary in that nuclear cratering is not employed in the present invention except in special optoexplosive systems such as that depicted in FIG. 2 or in near-surface bursts communicating their energies to the light leg 14*a*(having an open surface face) of FIG. 2.

For subterranean, contained nuclear explosions the usual law of scaling cavity radii is best modified for purposes of this improvement, as follows:

$$R = C\,(W^n/(\mathrm{ph})^m)\,k_{vent}\,k_{depth}$$

where

R = *cavity radius in meters*

W = yield in kilotons(1 KT = the release of 10^{12} calories or $4.2 = 10^{19}$ ergs)

p = overburden average density in grams per cubic centimeter

h = burial depth in meters

C = an empirically-derived constant generally ranging between 60 and 80 for available tests results

n = approximately 0.33

m = approximately 0.25

k_{vent} = an empirically-derived venting factor, usually a fraction of 1, determined largely by W taken together with the configuration of the optoexplosive system viewed in terms of fluid mechanics or hydrodynamic analogy; in a sense, k_{vent} can be regarded as that portion which departs from the ideal situation of a fully contained, non-vented ex-

plosion, e.g., when the shallow, subsurface cratering type of vented or semi-vented configuration is approached

k_{decplg} = an optional, empirically-derived(in certain instances, e.g., those involving directed energy or highly asymmetric CX or NX sources, and complex optoexplosive systems of large and/or loaded firing chambers with or without multiducted vents) thermophysical factor generally of value less than 1, which expresses the explosive energy taken up by decoupling mechanisms. k_{decplg} can enter the afore-mentioned equation when (a) the explosion chamber is large, e.g., due to lithoelasticity and like effects the seismic effect of a nuclear explosion can be reduced to an apparent nuclear explosion of ca. 10^{-2} magnitude; (b) there is emplaced cooperantly with the NX a decouplant agent or structure (blast and/or optical, depending upon the nature of the decouplant); and (c) sundry parameter interactions, as for example k_{vent} as just mentioned, the pressure P within the system and the nature of the radiative and collisional processes which make or break the local thermodynamic processes and their equilibrium of the P-medium loading the optoexplosive system; and the like.

In contemporary nuclear engineering directed to non-cratering results it is usually desired to prevent dynamic venting. This is done by NX burial equal to the anticipated chimney height of the cavity, while providing a 300 to 500 foot buffer of overburden. This can be used for approximating minimum burial depths of the explosive source, assuming the absence of vents engineered into the optoexplosive system. Thus, in the HARDHAT event of 1962 a 5 KT NX shot in granodiorite, at burial depth 939 feet, produced a cavity 63 feet in radius and a rubble chimney extending 281 feet above shot point.

In this invention vent adits and shafts function to relieve the system of blast and plasma, to valve-off or contain reactive or radioactive gases and debris. These vents may be surface exiting or, say in the case of high levels of radioactivity, are of a contained, dead-end kind. The primary function of vents and venting is to prevent non-wanted energies from getting into the light leg of the system and thence to the target.

For the aid of those skilled in the art and of interest in this connection is the HARDTACK series of five NX shots during October of 1958, as follows:

Event	Depth	KT Yield
TAMALPAIS	330 feet	0.072
EVANS	840 feet	0.055
NEPTUNE	99 feet	0.090
*RAINIER	790 feet	1.7
LOGAN	835 feet	5.0
BLANCA	840 feet	19.0

* The RAINIER shot is extensively used for the derivation of various scaling laws, including fully contained NX explosions, and is referred to herein for various parameters.

Otherwise, in the absence of extensive venting, decoupling, and use of multilegged means it is preferable to design and build a system very conservatively, say downwards by a factor of at least 100 per cent. A rule of thumb basis value, as indicated, from which minimum leg length(s) may be determined is the burial depth of upwards of several multiples.

The extensive literature on the PLOWSHARE program which is not practicable to cite in detail here(however, see Carl R. Gerber and Hugh E. Voress, A Selected, Annotated Bibliography of the Civil, Industrial, and Scientific Uses for Nuclear Explosives, U.S. Atomic Energy Commission, Division of Technical Information, TID-3522(rev. 8) May 1966; Proceedings of the Third Plowshare Symposium: Engineering with Nuclear Explosives, U.S. Atomic Energy Commission, TID-7695, 1964; The Effects of Nuclear Weapons, U.S. Atomic Energy Commission, 1962 and 1964 edns.; Peaceful Applications of Nuclear Explosives—Plowshare, Hearing Before the Joint Committee on Atomic Energy(Congress of the United States), First Session on Peaceful Applications of Nuclear Explosives—Plowshare, Jan. 5, 1965; and, especially for the artizen, the bibliographies in the aforementioned references including the extensive publications of the Lawrence Radiation Laboratory, University of California (Livermore) should be referred to for specifics).

Particularly as regards high yield optoexplosive systems the methods and means by which prevention or control of fluid excursions(gas and plasma) are attained may be conveniently, though somewhat arbitrarily, summarized and reiterated singly or in combination, as follows:

a. venting, as described herein, including ducts which originate at the shot point and shown along the explosion leg(e.g., 14 in FIG. 1, 40 in FIG. 3) arcing out say laterally from (and/or below) the explosion leg and around the FRO-carrying crotch portion so as to by-pass same, and feeding into the shock-sink leg(e.g., 18 in FIG. 1, 44 and/or 50 in FIG. 3) behind the emplaced FRO. Since the direction of flow is changed, work is done by the fluid and the total fluid energy decreases, so the laws of branching ducts and bends are appropriately taken advantage of;

b. venting by dilation or contraction, as for example contouring light leg 16 of FIG. 1 in conical, longitudinally-sectioned cone, or funnel geometry, with the apex or smaller portion of the cone joining in at the FRO portion; likewise, the shock-sink leg may be of conical or like diverging geometry. The result is that flow from the smaller explosion leg 14 of FIG. 1 into either or both of the larger legs 16 and/or 18 is accompanied by an increase in static pressure due to the decrease in velocity of fluid; the total energy of the system is decreased due to turbulence which takes place downstream from the crotch interface. I prefer that condition known as sudden enlargement so that head losses will be quickly and abruptly increased;

c. venting may be said to include burial at depths where the lithstatic pressure fails to contain the explosion and surface breakthrough occurs, as described herein;

d. venturi configuration of the system(cf. parent disclosure), wherein for example the explosion leg(e.g., 14 of FIG. 1) converges into a section coupled to the crotch, to form a throat, and a shock-sink leg diffuser(e.g., 18 of FIG. 1). Typically the throat diameter is about one-fourth to one-half the inlet duct diameter; for flow in one direction(as into the shock-sink), the included

positioned or of substantially slab or sheet form(e.g., 78 in FIG. 5 and one or more elements 84 in the same figure); thus, a "volume" or "bulk" FRO can be a block of lasing material(reflectively backed in the direction of the shock-sink) of the solid or liquid kind, which modification is described in detail hereinafter.

F. Passive and Active FRO: I distinguish the two classes as follows:

I. Passive(defined as an FRO which performs by virtue of the explosively-generated optical radiation, and is independent of other energy input), e.g., simple mirror FRO;

II. Active(defined as an FRO which performs by virtue of the explosively-generated optical radiation, concurrently being dependent upon an energy input from a secondary source which confers upon the FRO particular mechanical, thermophysical, optical or like characteristics which alter its response to the explosion light and, hence, alter the reflected explosion light), e.g., explosive mirror or self-destruct optic, hereinafter described.

The overlapping of the various classes of FRO means is most evident when the distinction between burnable, fusible, vaporizable and sublimable is attempted. As purely working distinctions of convenience, each is more properly defined within the frame of explosion light energy input, and whether the thermophysical changes-of-state or the thermochemical changes(molecular or the like) result from absorbed optical energy or from shock and blast kinetics.

The aforementioned classification is emphasized as an arbitrary one, aimed to aid the artizan by providing convenient working categories; and, at the same time, illustrative of the actual and potential scope of the new large class of FRO. Additionally, while examples of the simpler FRO elements are set out in the parent disclosure, e.g., plane and spherical mirrors and gratings, it is desirable to give further examples of FRO, especially those of the more complex and sophisticated variety and/or those which embrace unusual or little-worked portions of the optical spectrum. The following are by no means exhaustive of the family and its species.

The materials from which an FRO is constructed are usually solid. However, in unusual or specialty optoexplosive systems FRO members including fluids can be employed. For example, a sheet of reflective liquid, e.g., molten metal alloys of low fusibilities can be injected by suitable nozzle means, as for example via duct 28, to form the member 26, the angle being an appropriate one as long as optical coupling is maintained, in FIG. 1. Such modifications are the less preferable of the other more direct and easily reduced to practice forms of this invention.

The FRO means need not fit snugly or be neatly seated into position or have the same cross-sectional shape as the leg-conjoined or crotch portion of the system, e.g., as might be the case of an ovoid 26 FRO or a roundel(with ovoid frame) in FIG. 1. Thus, the FRO may not be of the same cross-sectional geometry as the leg(s) of the system, e.g., a polygon may be emplaced within a circular leg. The space open around a non-fit arrangement enables better sinking of the shock in high yield optoexplosions, also a more effective disposition of the FRO into the shock-sink.

Likewise, the FRO may be perforated or it may be in the form of a small-hole annulus, plane or curved in surface.

In special applications, e.g., shaped pulse production by the FRO, a train of FRO members can be employed, the hole member(disk) being at first offset(towards the explosion leg) followed by a second FRO annulus, and then by a larger-diameter third annulus, and so on, each to reflect and undergo destruction in sequence, starting with the center disk member. Each of the FRO elements in such a train may be of different substances so as to provide different fail characteristics and different reflection spectra.

When it is desired to linearly or circularly or otherwise vary the flux pattern across the face of the reflected light beam, several techniques can be advantageous. The FRO may be a composite of individuals of varying reflectances in mosaic or other surface pattern to correspond to the sectional energy-density desired, e.g., a mosaic of squares, slats, or concentric rings. Or a metal FRO surface can be selectively graded from highly polished to increasing degrees of roughness, whence to shift from specular through to increasing admixtures of diffusely reflected light. Or—in a sense the rough equivalent of this—is an FRO member having a wavy specular or polished surface; wherein one ray incident at a point is reflected at a first angle and another, say adjacent ray incident at a second point is reflected at an angle different from the first. "Flux-shaping", as I prefer to call this technique for purposes of convenience, is discussed in more detail hereinafter.

The blast-breakable FRO, e.g., sheet or foil metal, undergoes variable behavior in its "punch-out." This behavior depends upon such factors as blast strength, the nature of the FRO material and the mode of mounting, the pressure within the system, and the like. In tests I have found that overly thick metal FRO may be shattered, with strands hanging from the edges of the mounting. On the other hand, when the balance between FRO strength (e.g., thickness) and the method of mounting(e.g., as when a series of "break holes" are made at the periphery of the FRO mount, a rather curious but not unexpected phenomenon occurs when the balance between blast (at atmospheric pressure) and metal foil are just right. The FRO is very cleanly punched out and is often found at the bottom of the shock-sink as a neatly self-wrapped, crenated ball. Of course for highly brittle or shatterable FRO materials this does not take place, the result being a simple mechanical fragmentation. The balling effect is due to the rarefaction component which travels immediately behind the shock front, the positive pressure front causing the metal to collapse inwardly upon itself and so form the interesting ball.

In modifications of this and the parent invention where shock or blast-ruptured FRO elements comprise the system, the artizan will be aided by existing knowledge on bursting diaphragms. Reference is made to J. Seremak, "Diaphragms: A Selected Bibliography," Clearinghouse for Federal Scientific and Technical Information(abbreviated CFSTI herein), AD 623,361, October 1965. The period of 1920 to 1965, with 135 references, is covered.

The large deformation, e.g., from plane to dome, response of a simply-supported, inelastic, circular

angle of the convergent inlet cone should approximate 20° to 22°, with the included angle of the diffuser cone approximating 5° to 10°. Turbulence can be designed into the venturi configuration by making cone angle and/or the diffuser angle overly large, which is frequently desirable when high Mach fluid of explosion origin is to be degenerated(i.e., when large kinetic energies are to be dissipated as thermal energies in the shock-sink).

e. "anablastic"(anechoic analog) wall projections within the explosion leg and/or shock-sink leg, as described, to enhance fluid power drop by wall-friction type and similar mechanisms;

f. ablatives within the explosion leg and/or shock-sink leg, as described, and which may comprise naturally ablating tellurian material(silica, feldspar, dolomite) or those incorporated in the form of slowly disintegrating anablastic means, wall liners, casings, and the like; impelled 7, employed

g. droppable or impelled valving systems such as set out in FIG. 7, employed singly or in plurality along the explosion leg 104;

h. directed-energy explosions such as set out in FIG. 8, employed singly or multiply along the explosion leg 118;

i. choice of proper explosive charge sizes consistent with tunnel lengths;

j. use of asymmetric explosions, considered hereinafter;

k. optoexplosive system design incorporating fluidics principles, including series orifices(cf. (b) and (d) supra), the subject of a large literature available to the artizan;

l. systems design in which the different legs are in different attitudes with respect to each other, i.e., spatially rotated and not in the same plane;

m. liberal employment of zig-zag, blind-alley and comparable configurations, like that depicted in FIG. 3;

n. and the like.

FRANGIBLE REFLECTIVE OPTICS

The frangible, reflective optic(FRO) is an especially important element in this invention. A large number and wide variety of FRO means can be designed into the system. The types and kinds of optical performance embrace much latitude, corresponding to the many and diversified attributes of the FRO, comprising what I believe to be a new and unique family of optical devices.

For purposes of orientation the parent disclosure, Ser. No. 407,461, includes the following statement:

"By frangible optic I mean a member which, upon being struck by the light energy from the explodable light source . . . routes that light energy as light . . . freed of shock and like non-optical forms of energy into the light leg . . . and thence into the irradiable target.

". . . the term "frangible" will be equivalent to "breakable," "destructible," "burnable," "sublimable," "vaporizable," and the like. The reason for this is that the "frangible optic element" . . . e.g., mirror, can have qualities other than simple mechanical frangibility or breakability. Thus, the mirror can be simultaneously reflective for say the visible portion of the electromagnetic spectrum and absorptive for the infrared, the latter causing the sublimation, burning, vaporization or the like of the mirror member. Although the two radiations have the same velocity, reflection occurs first with a time constant of the order of 10^{-15} second or less, whereas burning, sublimation, ablative and like mechanisms take longer, e.g., greater by several or more orders of magnitude, because heat transfer is slower and change of state processes are slower; pure and simple reflection, for example, involves no change of state, whereas absorbed energy requires time to manifest itself as change of state, e.g., to vapor, reaction products, sublimone, or pyrofragments."

This of course means that the FRO as originally set out includes varieties which are other than simple blast-breakable and, by the same token, the operating principle of my explosive light generator may be other than that of simple light reflection-shock destruction sequence. A_s pointed out, the reflection time is of the order of 10^{-15} second, which changes of state or, at the least the cessation of functioning as an FRO, several or more orders of magnitude less; the best values I have been able to obtain for reflection time is 1.2 femtosecond for the widely used reflectant aluminum, obtained by Drude formulas.

Herein I refine and amplify the nature and characteristics of the FRO as a class of optics. Several working categories are convenient(albeit occasionally overlapping), for the one-shot or multiple-feed FRO which, in turn, may be fed into the optoexplosive system rotationally or translationally (preferred in this improvement), as originally disclosed, as follows:

A. Cross-section Geometry: The FRO is usually circular or a roundel corresponding to the sectional profile of the system, or, of such suitable geometry as to adapt to emplacement at the conjoining portion.

B. Optical(surface) Geometry: A variety of choices are available, as for example:
   i. plane surface(e.g., mirror);
   ii. curved surface(e.g., concave or convex mirror-lens);
   iii. other(e.g., fresnel mirror, parallel or circularly ruled, reflection grating).

C. Physical: This category includes, for example:
   a. rigid FRO;
   b. elastic or deformable FRO.

D. Thermophysical: FRO means responsive to absorbed light with cessation of performance as a reflective optic, including as previously mentioned:
   1. burnable;
   2. vaporizable;
   3. sublimable;
   4. fusible;
   5. other.

E. Optical Configuration: For example:
   x. simple optic(e.g., plane or spherical mirror);
   y. compound optic(e.g., active or passive optical medium(cf. below) backed by reflective member, or a stack or sandwich of materials of different optical characteristics backed by reflectant; may be plane, spherical or other surface or interface geometry);
   z. "bulk"(by this designation I means a volume of optical material which need not be angularly

membrane(i.e., FRO) which is subject to blast loading (usually from spherical or symmetric CX charges under water) has been investigated upon theoretical and experimental bases by Donald Boyd (Presented at the Third Martin Symposium on Solid Mechanics, 2–4 June (1965), Denver, Colorado (114 pp.); AD 830,109). This analysis is especially relevant to what may be termed "quasi-timed-life" FRO elements wherein, for example, the FRO is a reflection grating which, under blast loading and consequent spheroidal deformation, shifts its spectral output between blast impact and blast destruction.

The rupture strength of ductile metals subjected to pulsed loading(shock) has been investigated by Vitman et al. (Fizika metallov *i* metallovedeniye, 18(5):717 –723(1964)), with pulses of 10^{-5} to 10^{-6} second. Metals like copper, aluminum, lead and ferrous alloys are arranged generally in the same sequence as that formed by their values of static crack strength, with some deviations.

Experiments on time and failure on about 50 different materials has established that failure occurs under loads which do not attain the limit of strength, the lifetime of the materials being inversely proportional to the load, according to an analysis by Slutsker(Priroda, no. 8,36–42 (1965)).

Consistent with the FRO ball-forming phenomenon set out herein, the metal failure under explosion force is not a permanent characteristic of its strength; it can undergo a wide range of changes depending upon the strain rate in the interacting rarefaction waves. The dynamic yield strength is apparently determined by the position of the minimum of the metal expansion curve in the area of negative pressures (e.g., of its theoretical tensile strength, according to Al'tshuler et al.(Akademiya nauk SSR. Doklady, no. 1, pp. 67–70(1966)).

For abstracts of the above and 105 other items relating to elastoplasticity of FRO metal candidates, particularly high parameter energy and matter interaction, reference is made to: "High Parameter Energy Matter Interaction," Surveys of Foreign Scientific and Technical Literature, ATD Report 68–14–72–1, AD 660119, Aerospace Technology Division, (US) Library of Congress, Washington, D.C., dated 23 October 1967, 59 pages.

Because of their mechanical frangibility frozen liquids make excellent FRO elements, at the same time providing reflection spectra not easily obtained by use of conventional solids. For example, I have made FRO members in slab and mirror lens from by freezing water in its pure state, with aluminum particles in suspension ("aluminized ice"), and with aluminum foil backing. In every instance, when inserted into the test model of the optoexplosive system, small chemical charges(e.g., black powder doped with 10–15 percent aluminum powder) readily fragmented the ice FRO and shot its debris down the shock-sink. Reflected visible light could easily be seen, and infrared pulse observed through filter by an image converter. The infrared pulse evidently corresponds to peaks of reflection for ice at 3.2 microns and 13.0 microns, with other wavelengths contributing accordingly.

Note is made of the fact that restrahlen or "residual" rays occur in the reflection spectrum of ice near 13 microns. The subject of the FRO as a reststrahlen monochromator is discussed subsequently.

Suffice to state that clear frozen water(ice) is an example of an FRO characterized as a frangible reflective optic operant upon the well-known fresnel law of reflection wherein two or media of different refractive indices(in this case air and ice) form the FRO. Thus, by definition an FRO need not carry a metal or silvered or like foil or coating, although this is usually desirable from the standpoint of obtaining optimum reflection.

An FRO can be operated at the extremes of temperature, as in the case of an ice mirror, or molten metal sprayed in sheet fform or allowed to run over the light incidenting surface of a suitable substrate. High or low temperatures, particularly the latter, may be desired when it is necessary to alter the physical-mechanical characteristics of an FRO(e.g., plastic cooled to the glass point so as to be highly brittle), when chemical properties and practicability dictate(e.g., otherwise highly toxic or corrosive liquids in the frozen, solid state), and when certain optical properties are to be enhanced(e.g., alteration of electron or lattice energies), and the like.

The heating or cooling of an FRO is best accomplished by use of a conventional system which includes a hollow backing member or series of pipes having inlet and outlet conduits in communication with the source of the heating or cooling agent residing at the surface(e.g., 20*c* in FIG, 5). Molten metal, hot liquid(pressurized or not), or liquidified gas is circulated through the system and the FRO brought to the desired temperature point. The system itself should be frangible and, therefore, is usually constructed from light metal; alternatively, peripherally mounted pipes can be employed, or a concentric(and spaced) piping used, particularly for large area FRO members.

Alternatively, for fast heating to relatively high temperatures, as in the case of a fusible metal or alloy which is to act as the reflecting medium, a pyrotechnic heater. These explosive heaters are one-shot devices which consist of an actuating igniter and a piece of steel tubing containing a pyrotechnic, heat-generating composition. With a surface temperature of the order of 700°C such a heater can furnish 0.625 Btu/in. at a rate of 4 to 5 seconds per inch. They can be had in long lengths, and several sections can be connected together. The pyrotechnic heater can be bent into almost any desired configuration, e.g., plane spiral, for attachment to the back of the heatable FRO, or for immersion in the FRO medium, as may be desired. Large, non-round specialty pyrotechnic heaters of greater Btu output and controlled temperature (increased if wanted), as well as burning rate, can readily be designed. See Machine Design, 4(16), 116–122(July 4, 1968) for further information.

If in FIG. 2, the explosion leg 14*a* and the light leg 16*a* are say 45° with respect to one another(the shock-sink leg 18*a* continuing on through from 14*a* in line-of-sight to 34*a*), the FRO means 35 may then be placed horizontal or parallel with respect to ground surface 20*a*. In such a configuration the FRO means can then comprise an open-faced liquid reflector. This may be carried as an appropriately thin layer within a frangible pie-plate or like pan or tray container.

The liquid reflector may be the clean, freshly-fused surface of a metal, for example; such a metal may be a low melting point alloy or it can be fusible metal which liquifies at higher temperatures, e.g., Ag, Cd, Zn, Au, Pb. Heating is done in the usual way, as by high temperature heating elements beneath and around the FRO ensemble. When oxidation and dirty-surface filming present a problem because of the presence of air, hot gas like nitrogen or helium may be blown across the face of the molten reflector.

When it is desired to have an FRO element which is highly refractory or is material that is selectively temperatureresistent(e.g., in which the parameters of melting point(or vaporization, sublimation or decomposition), specific heat, and thermal conductivity interplay to provide the ultimate performance profile), or in the case of a timed-life FRO (where built-in or controlled failure is desired for modulating or demodulating the incidenting light pulse or pulse complex), or in the case of an FRO which is to exhibit change in reflectance and/or reflection spectrum through the time of the incidenting event, a number of substances can be advantageously utilized. These may be worked in a cryogenic state or at elevated temperature(as by resistence heating), to preferentially alter optical and/or mechanical properties.

These FRO substances form a very large class, usually inorganic in nature, including metals and metalloids in the elemental state, borides, carbides, nitrides, single and mixed oxides, sulfides, silicides, various metalloid compounds, and intermetallic compounds and alloys, as well as specialty ceramics and glasses(which may or may not be colloided by optically active additive(e.g., absorbing particles of metal blacks) or reflectively backed when a high degree of fresnel reflection is to be avoided). The materials run the gamut of color between white and black, with pure and mixed, variegated colors in between.

For candidates of this class of FRO substances the artizan should make particular reference to compilations like that of J.F. Lynch et al.("Engineering Properties of Ceramics: Data-book to Guide Materials Selection for Structural Applications", Battelle Memorial Institute, Columbus, Ohio CFSTI AD 803,765, 688 pp., 1177 + refs., June 1966), wherein there is tabulated some 800 substances and upwards of 20 physical, thermal (table 4.3.2 lists about 600 materials according to melting point, including incongruent melting (which is of interest in connection with timed-life and variable-reflectance FRO means), vaporization and sublimation, and decomposition temperatures), mechanical, stress, and oxidation and corrosion properties. The temperature range is between about 1 and 7×10^3 °C, the latter being represented by the melting points of such substances as Ta_2C, ZrC, NbC, TaC, and HfC. Optical data like reflectances and reflecion spectra(including the extra-visual spectrum) are not given, and the literature cited should be consulted for what sparse information may exist on this facet of materials properties.

When an optical energy-disintegrable(burnable) FRO passes into its destruct phase, due to the time-varying deposition of light therein, there is a shift in (a) reflectance efficiency and (b) spectral nature of the reflected light. A simple example is an initially white or highly reflective, disintegrable (or vaporizable) FRO material which ends up black (and, finally, physically destroyed), exhibiting gradations in reflectance and of color(or, more accurately, reflection spectrum), e.g., through yellow to brown in the familiar burning process. This behavior is decided by the FRO substance and is generally more characteristic of initially heat-resistent substances which degrade through light pulses of long duration and relatively low flux.

This lays the basis for a special modification of the "-burnable" FRO, which may be said to correspond to photochromic and thermochromic phenomena observed in such substances as mercurous fluoride and the double mercuric iodides, $HgI_2 \cdot 2RI$(R = Li, Na, K). The artizan is referred to the large literature on photochromism and thermochroism for additional examples and details.

Another reflection modifying or shifting FRO is that of a burnable or change-of-state(vaporizable, sublimable) overlay substance on say a temperature resistent FRO substrate. The top layer may be only lightly bound to the substrate, the two having different different heat response properties, such that the overlay peels, spalls or otherwise breaks away so as to expose the substrate FRO, which then functions until it too is destroyed. The time constants of these types must lie within the input pulse duration, and the change-of-state be fast enough to enable the substrate FRO to come into play at some useful point in that pulse.

With the injection of extremely large amounts of optical energy within very brief periods into an FRO of small mass, e.g., of thin-film type, that FRO can be expected to literally explode. In certain ways this may be said to be the optical analog of the exploding wire phenomenon. For example, on general thermodynamic grounds the high temperature matter should show vaporization waves, which is shown by various metals including frozen mercury(which can be utilized as an FRO element in this improvement) in the electrically exploded conductor effect, as well as the various fluid dynamical phenomena perculiar to that effect. Wave speed models and thermodynamic interpretations based upon the little available knowledge about vaporization waves are highly suggestive of method and means for the utilization of vaporization waves as the basis for a specific type of timed-life FRO. A theoretical background on the subject can be had by sterting with: F.D. Bennett, Phys. Fluids, 8, 1425(1965); G.D. Kahl, Phys. Rev., 155, 78(1967).

Included in the category of fusible FRO elements are those which are shock-fusible. Theoretically shock wave compression-fusion follows from the conservation law, and the calculation of the fusion curve is based upon the volume and fusion temperature interrelationship. Analysis by Urlin et al.(Akademiya nauk SSR. Doklady, 149(6): 1303-1306(1963); cf. p. 7 of ATD Report 68-14-72-1 cited herein) shows that by careful mechanical shock wave measurement the intersection of the shock adiabatic curve and the fusion curve can be adequately determined if the slope is not overly steep.

Taking the case of an FRO element of lead, fused by shock, as described by Belyakov(ibid., 170(3):540-543(1966); ibid., abstract 23 on p. 14ATD Report)); thusly: Since the thermodynamic parameters of a sub-

stance in a shock wave do not change materially, it is impossible to distinguish the shock adiabatic curves for heating a substance in its solid and its two-phase states by measurements of wave and mass velocities. Lead has a substantial thermal expansion, low fusion point, and tendency to non-polymorphism.

The mass-equivalent velocity required for the melting of lead is approximately 650 meters per second, corresponding to about 23×10^4 atmospheres pressure and a volume increase of between 22 and 23 percent. With a 2 millimeter lead sheet, as in the case of an FRO, the fusion takes place at about 1250 to 1300 meters per second; for 1 millimeter lead sheets the value is 1340 meters per second. Like the punched out FRO(i.e., cleanly made roundel of aluminum, metallized paper) I have observed in my tests, there is the splitting-off of a saucer-shaped layer(i.e., from the side opposite of impact).

The FRO may be elastic under mechanical or thermal loading so as to be of timed-life nature. For many materials used in the make-up of an FRO deformation obviously occurs upon shock insult or heat deposition at very high rates. However, it may be desirable for cut-off of the light pulse(derived from the explosion) at some point in time to have an "elastic" or thermally-deformable(warping, buckling, and the like) member whose optical surface(e.g., planeness or sphericity) is altered in a controlled manner.

Conversely, the FRO may initially be out of optical coupling with the explosion leg and/or light leg-target, so the function of an elastic FRO in this instance is to optically couple by form change source of light(CX or NX) and/or target.

Such an arrangement is adapted to chopping out a segment of the explosion light pulse beginning at a time later than the birth time T(e.g., of FIG. 6) of the explosion. This in effect enables the by-passing of unwanted early optical radiations corresponding to the leading edge of the source pulse. This may be desired when short wavelength radiations characteristic of the early, formative stage of the explosion are to be screened out.

This variety of FRO can be of one substance in contiguous form; or, a mosaic of various substances of different properties, for example. Likewise, the substrate, if any, or the backside support means(e.g., grid), if any, can be designed into a more complicated form of deformable, timed-life FRO. The material(s) employed is chosen mainly on the basis of elastic modulii, particularly at elevated temperatures where thermal energy from the input light causes abrupt excursions, and hence of form. Polymers, especially silicone or other metal-organic and fluorinated, metals, and glasses and cryptocrystalline ceramics can be used. The FRO of this type can be at either elevated temperature or in a cryogenic state, depending upon the substances and the structure.

The dynamic behavior of impulse-loaded(shock but preferably thermal) deformable, timed-life FRO means embraces a large number and wide variety of disciplines and technologies, no small number of which involve a good deal of empiricism. For example, seals and diaphragms, vibrational and waveform analyses of damping, mechanical and thermal dynamic properties of materials, and the like. This is a very broad subject no feasibly gone into detail herein, so the artizan is referred to the relevant literature. For spherical optic types of FRO elements the equations of De Luca, for example, can be used as starting approximations. Otherwise, such problems are evidently best approached by computer analysis.

As originally disclosed, the FRO may be a reflection diffraction grating, usually a replica. This may be of the usual kind, linearly or circularly ruled and coupled to appropriate slit or onion stop at say the exit of the light leg, or, a series of such gratings can be employed(e.g., 78 and 84 in FIG. 5). However, for the far infrared, e.g., in the region between 10^2 and 10^3 microns, a wire grating can be utilized. This and the transition region are usually considered difficult for experimental work, partly because of the paucity of radiant power available from the more conventional sources, making for a considerable signal-to-noise problem. The wire grating can also be used as a reflection polarizer for the regions indicated.

Wire gratings exhibit interesting characteristics in the transition region between the infrared and the microwave, where the wavelength is approximately equal to the grating spacing. Note is made of the fact that transition energy is included in the output of NX explosions. Wire gratings and their theory for the long wavelength and transition regions are described by Wessel(Hochfrequenztechnik, 54:62(1939)). Large area wire gratings suitable for use in this invention can be made by scribing metal-coated dielectric substrate (e.g., plastic, glass, fused silica).

Narrow band or essentially monochromatic explosion-derived light can be obtained by means other than the reflection grating(absorption filters are generally less desirable because of working limitations, although the refinement of compound FRO elements discussed herein can be used). Thus, the FRO can take the form of a reststrahlen optic. Typically this is a plane or spherical mirror of the FRO kind having a first surface coating of material which provides reflected residual radiation. The coating is usually in crystalline form, sintered, pressed or minimally cemented as a coating on the substrate. Such devices are worked in the infrared. Examples of materials include sodium potassium niobate(11 to 40 microns), and cesium iodide and cesium bromide(120 and 170 micron peaks). Structurally such FRO elements may be considered in the class of the compound FRO.

The FRO need not be of plane or spherical surface contour. It can have a bulk or volume geometry when it is desired to include lasing material, for example, adapted to pumping by explosion light. Illustratively, in FIG. 1 member 26 is set parallel to the axis of leg 16; at the light input 34 or face of 26 there is positioned a square, rectangular or other appropriate bulk of lasing substance. Light 34 enters the lasing substance and reflects back thereinto, giving a side pumping. The lasing material may be stacked rods of solid laser material such as ruby, Nd activated glass, or the like. The laser light exit ends of the laser stack align parallel to leg 16, to impact target 30.

Alternatively, the laser may be a liquid carried within say a silica cell backed by FRO at say the Brewster angle. The silica cell is usually plane at the front(facing the incoming beam 34, which pumps), and may be of rectangular or square or circular side wall geometry,

enclosed at its top by the exit or portal(which may be plane, i.e., parallel to axis 34, Brewster or other angle, again to issue the laser beam up and through leg 16 to target 30. In order to enhance lasing efficiency, also frangibility(secondarily), the laser liquid may be supercooled.

An extensive listing of laser substances is set out in the parent disclosure, including liquid lasers substances like rare earth chelates. A contemporary liquid laser of higher efficiency than those originally described is the aprotic solution of neodymium salt dissolved in an acidified solution of selenium oxychloride. Not excluded from the FRO version described supra, wherein the FRO is faced by a cell containing optically active material, are those agents which are marginally responsive to the pumping levels of present light sources, e.g., so-called Raman lasers and Brilluoin lasers.

Not excluded are gas-loaded cells carrying gas or gas-mixtures well known in the art which can be made to lase by optical pumping. As in the case of liquid lasers the gas lasers may be in the configuration of a solid cube, rectangle, or the like.

Likewise, the FRO backing member need not be in intimate association with the bulk lasing substance. The FRO may be set back therefrom and may, in such an ensemble, be non-plano in type, e.g., ellipsoidal, so as to reflect explosion light back into the laser.

A detailed analysis is not necessary to demonstrate that a CX or NX light pumping involving a laser is adequate to produce (a) laser pulse energies far exceeding those now attainable or feasible with the various electrically-driven discharge pumps, e.g., double- or multiple- pulsed, high-pressure flashlamps, zeta and theta discharges, and ablative light sources, particularly taken with the aperture or laser beam diameter (b), which may lie in the range of several tens of square feet.

When non-destructible laser pumping is desired, then the target is the laser, as for example 30*c* in FIG. 4, wherein the laser 30*c* at any appropriate attitude with respect to shock-free, pumping beams 64 and 72, is excited by multiple inputs; 30*c* can be surrounded by retroreflective mirrors. An asymmetric, e.g., cruciform, optoexplosive light source is preferred in the multilegged system depicted in FIG. 4.

The lasing and fluorescence-transducing FRO ensembles are examples of the "passive" FRO types of the previous classification in that they function independently of energy other than optoexplosion light. Upwards of 20 such physical effects involving electromagnetic radiation impinging on matter, which are of interest in connection with the present subject, have been described and tabulated by George Raabe("A Selection of Physical Effects and Their Description: Appendix(Part IIIa), CFSTI AD 276,381, Rept. No. SMIR 62-5, 130 pp., 1962(67 physical effects are clearly and succinctly described, not all of which I note are applicable to the design of compound FRO elements of either passive or active kinds because of constraints placed by materials, energy(e.g., large magnetic fields), low-order effects, or the like, but which should be surveyed by the artisan in any event); "A Selection of Physical Effects and Some of Their Implications in Recent Materials Research," Part III, CFSTI AD 272,930, Rept. No. SMIR 62-4, 8 pp. + 6 tables, 1962(see especially Table 2A)).

In an "active" FRO ensemble energy is supplied so as to give field-controlled electromagnetic energy propagation, the supplied energy being other than that created by the optoexplosion. Field-control is usually the result of electrical energy fed to a responsive substance comprising the FRO and, to a lesser extent, input acoustic energy. Because of size and mass an other working limitations field-control by magnetic energy is generally limited to smaller optoexplosive systems equipped with small area, active FRO ensembles.

Thus, Table 2B of the Raabe publication(Part III) details upwards of two dozen physical effects which are field-controlled insofar as electromagnetic propagation is concerned. Again, it is not deemed necessary to detail the specifics of each and every candidate phenomenon, other than to point out that certain of these will be readily recognized by those skilled in the art as incorporating novel behavioral attributes into an FRO member. These behavioral attributes include spectral shaping, polarization, oscillation and vibratory qualities, light switching, spectral transduction, and the like. Examples of the physical phenomena include, for example: piezoelectric effect, Cotton-Mouton effect, Kerr and Pockels electro- and magneto- optical effects, magnetostriction, and electro- and magneto-photochromism and thermochromism(not described in the reference).

A typical active frangible, reflective optic is a mass, say a slab roundel, of high detonation velocity chemical explosive. Such an explosive FRO is a self-destruct device which can be made to fail at any desired point from immediately after the initiation of the optoexplosive CX or NX source to the arrival of blast and shock. These performance parameters enable the self-destruct FRO to cut in on the CX or NX light pulse at any desired time, chopping out a sinusoid, so as to reflect a shaped light fragment which is time-intensity modulated.

Illustratively, an explosive FRO is a cast or pressed suitable explosive slab which carries on its face a metal reflector, e.g., Al, W, Au, say of thin foil. The explosive substrate, in this simpler version, carries at its edge or inserted into the periphery a series of detonators(with or without boosters, as required); these are fired simultaneously, to cause the explosion and self-destruction of the FRO. The timing of the firing is determined by the size and geometry of the explosive mass(which may be plane or non-plane), its detonation velocity, the point of CX or NX light pulse interruption, and like factors.

For example, a roundel of mannitol hexanitrate, having a detonation velocity of approximately 8000 meters per second, of 1 meter diameter and 2.5 centimeters thickness, is provided with between 8 and 24 detonators or electric igniters, requires about 4 milliseconds for self-destruction. If spaced detonators are placed close together on the backside of the explosive roundel, the explosion life of the mass can be reduced to the submillisecond realm.

A somewhat more complex explosive FRO can be employed when very fast self-destruct times are required. Typically, this comprises a hoop or ring of shaped charges, the cone or jet faces of which are all aimed at the center of the ring(in or not in the same plane, as required by the geometry of the FRO). Over

the hoop of shaped charges or emplaced within the ring is destructible reflective solid, such as thin polished metal sheet. The simultaneous explosion of the charges produces exceedingly high velocity jets which give the FRO a disintegration time in the nanosecond domain.

An unbalanced explosive charge ensemble can be employed, shaped or not, to destroy only a part of the FRO, leaving a subsequently-destroyed portion, the combination of the two or more portions acting to intensity modulate(by reflection) the incident optical beam.

As desired, the explosive FRO can be heat-ignited by the impacting explosion light; copper, graphite or other heat-conductive metal "squibs" are partly embedded in the explosive, with a portion extending out into the oncoming beam.

The explosive can be liquid encased in a frangible container, e.g., nitroglycerine or nitromethane in thin steel, aluminum, plastic.

Following are explosives of high detonation velocities adapted to use in the explosive, self-destruct FRO, in the case of solids the values differing somewhat according to density as well as method of test, but representative:

Explosive	Detonation rate (meters/second)
Mannitol hexanitrate	8250
Nitroglycerine(metal container)	7800
Picric acid	7350
Tetryl	7850
Trinitrotoluene(TNT)	6640
Tritonal(80:20 TNT/Al)	6700
Cyclonite(RDX)	8180
Nitromethane(container)	6200
Pentaerythritol tetranitrate(PETN)	8300
Pentolite(50:50 PETN/TNT)	7500
Cyclotol(75:25 RDX/TNT)	8000

Preferred as the optoexplosive light source for this improvement are:

I. Chemical explosives and explosive compositions(CX);

II. Nuclear explosives and explosive compositions(NX);

III. Combinations of the two.

These may be (a) symmetric in that their energy release roughly corresponds to a "point source", as from a spheroidal mass of explosive, or (b) asymmetric in that their energy release is characterized by taking a particular direction (directed-energy explosion), as from a hollow or shaped charge. Combinations of the two, (III) supra, may involve interaction with or interruption of the primary optoexplosion by secondary explosion, usually directed-energy in nature(e.g., CX) as described hereinbefore for the accompanying FIG. 8.

The parent disclosure gives examples of optoexplosives, and I refine and expand upon this facet of the subject in the following.

CHEMICAL OPTOEXPLOSIVES

CX energy sources are variegated and of large number, including individual substances, combinations of materials and reactions having as a primary quality the liberation of very large amounts of energy, both kinetic and electromagnetic. These can be tailored to, and explosives ensembles and systems designed for, maximization of light generation and minimization of blast and like kinetic energy.

Compounded upon the plateauing of light outputs practicable with the various flashtubes available, constraints are further placed upon the generation of very high energy, ultrahigh power light generation by the limitations of large primary power storage systems. These constraints and limitations inherent to the electrical art include inordinate size, weight, bulk and a lack of portability, as well as severe restrictions in time and place. One answer to this problem is the seizing to purpose the energy stored in an explosive. Thus, figures in the art give a 5×10^4:1 saving in bulk, size and weight of chemically-stored energy over capacitor-stored energy, although in many instances this has to be revised downwards by one or two orders of magnitude to be realistic.

Herein I supplement and expand upon those CX light sources originally disclosed, giving special emphasis to what I believe to be unique approaches to the subject of optoexplosive technology, in line with my continuing theoretical and experimental studies of: (a) methods and means for the seperation of light from blast in an explosion, and (b) optoexplosives per se, together with the designing of those optoexplosives into means by which optimum light generation is obtained.

Since it is not feasible to here detail the explosives art other than to emphasize areas of especial interest to the artizan from the optoexplosion viewpoint, I would reiterate what is stated in the following section on nuclear optoexplosives; namely, that a preponderance of the existing body of knowledge on explosions relegates optical phenomena to a secondary or often in absentia role. The computer rundowns for information retrieval I have had performed turn up a scarcity or complete absence of data on optical energy generation in explosions, the radiant energy and spectral qualities of which otherwise would be of considerable pragmatic value. The striking paucity of data on optical energy inherent in other-parameter-monitored explosions of the large yield kind perhaps points up the fact that, traditionally, chemical explosions have been and are first and foremost blast energy workhorses.

The foregoing is a critique which in oversimplification relates to detonation light as contrasted to shock-wave light. There is a substantial body of literature on the latter subject. I regard an optoexplosive as an agent which performs out of detonation light and, to a lesser extent in most instances after-cumbusting light, although certainly not excluded from the meaning of the word is shock light. The reason for this is that detonation light is essentially independent of its atmosphere or environment, e.g., the process can occur in a vacuum, whereas by definition shock light is environment-dependent.

For high explosives the physical and chemical processes are actually not this simple, and the demarcation is not always clean-cut, for there are complex interdependencies and interrelationships between detonation light and shock energy and the afterburning explosive substance. For low explosives detonation and shock contribute to a much lesser degree to the light generation, while combustion-like processes play the dominant role.

Despite this rather easy approach, the distinctions do serve as a working basis for the development of improved optoexplosives, and for their implementation in the problem of shock-light separation.

Chemical optoexplosive light sources can for present purposes generally be considered as broadly of two kinds:

1. Molecular(or single-substance) materials, which may be solid, liquid or gas in form, or combinations thereof(as when not in intimate admixture or when employed in groups, the individuals being regarded as substantially non-interacting in the explosion process);
2. Multisubstance(or ingredient) compositions, which may be intimate admixtures, solid or liquid or gas solutions, or sorptives or the like, which may be solid, liquid or gas in form, and which may comprise binary, ternary or like formulations of the explosives art, particularly those which have been redesigned physically(as by increasing the density), chemically(as by introduction of a light-emitting metal into an organic molecule), and/or stoichiometrically(as by raising or lowering the fuel-oxidant ratio in say a nitrate or chlorate-metal admixture).

Thus, taken together with the original disclosure, Ser. No. 407,461(filed Oct. 29, 1964), the following may be taken illustratively and typically as optoexplosives together with methods and means for stimulating their output in the optical spectrum.

Molecular(or single-substance) explosives include those of the usual variety, e.g., polynitro- organics such as TNT, RDX, PETN(and others listed elsewhere herein(as in the table of detonation rates)) can be employed per se but, preferably, these are modified so as to enhance light output and reduce the proportion of kinetic to optical energy released. These substances are primarily designed for blast effects. Thus, by lowering the density of an explosive of this kind the detonation rate and, hence, the light contributed by afterburning appropriately raised.

For example, conventional high explosives of the molecular class can be physically treated so that in a cellular mode, e.g., foamed, where air or other gas interstices contribute to density reduction, the performance is markedly altered. In addition to cellulation by foaming, other techniques include binding the explosive particles with an elastomer, drawing into strings or threads, weaving these into an "explosive fabric", and then fashioning the optoexplosive element from this fabric, which fabric may have interstices of any desired opening size. The explosive fabric can be wound upon itself from yardage of the same, or randomly aligned woof and warp stacks made by piling one sheet on top of the other, to form the optoexplosive "-pile". As desired, such a mass can be impregnated with liquid explosive, liquid or colloidal dopant, or with solid dopant.

"Area CX" energy sources provide an approximation of a Lambertian radiator when the interstitial or cellulant explosive sheet(e.g., fabric, hole-punched sheet, or spumed sheet) is hung vertical to the axis of the firing leg and within its explosion vault or portion. Such area-explosives, which may be sheets of circular or other desired form, may be hung flat, or they may be hung after the manner of drapes in pleated, folded or accordianized contour. A plurality of such sheets is preferable, in contact or closely spaced, behind one another, so as to build the required mass of optoexplosive. The sheet surface may be coated with dopant or the spaces between the various sheets may be occupied by dopant in sheet form, as for example foil of Al, Mg, Zr, Hf. Alternatively, warm(so as to rise) gas like He, Ar, Xe, Kr, and Ne, may be fed by an appropriate series of nozzles at the bottom of the area-explosive ensemble, to contribute to intensity or spectral shaping upon firing; likewise, reactant gases may be utilized, as well as warm convection-rising vapors(inorganic(e.g., tetrahalides like the chlorides or iodides of tin, silicon, germanium, or substances like uranium hexafluoride), metal-organics(like certain of the Grignard compounds; cf. those for hypergolic reaction set out herein), or organics(e.g., high carbon content gas from polycyclic hydrocarbon sublimones). By fusing means well known in the art, an area-explosive can be made to detonate substantially simultaneously, or such a detonation can be time-delayed as regards the components; the latter situation will be recognized as one which produces optoexplosive pulses of longer durations.

When the CX material is sensitive to impact, friction or electrostatic charge, special precautions must be taken in loading the system with large masses of the explosive. Pumping in as a slurry, and then dewatering and drying in situ is practicable in many cases, and this is gone into subsequently in the discussion on sensitive optoexplosives like the azides. When slurry-loading is not feasible the firing portion or vault in the explosion leg can be modified in: (a) atmosphere and/or (b) underwater or under-oil loading, for the building of a pile of explosive..

Slabs or bricks of static-sensitive explosive, which may or may not be coated with thin, electrically-conductive plastic, are built into the explosive pile in say an atmosphere of conductive ammonia gas or organic amine vapor, this to be subsequently outpumped when the pile is completed.

Racks or like structures may or may not be employed in stacking large numbers of explosives pieces.

When the explosive is impact or shock or friction sensitive, it can be loaded under water or under oil, both providing cushioning, and the water conductive, as may be desired. Thus, a small coffer dam, crib-coffer, or canvas-plank bulkhead container is made within the firing chamber and then filled with water or oil; grillage, piers or the like may be employed. The coffer structure may have a neck extending up the loading hole, to ground surface, the hole also being filled with liquid. After loading the liquid is pumped out and the coffer gently taken apart.

The foregoing coffer dam and like technique is designed for making explosive piles of large mass and size, e.g., say 10 tons or more. For quantities less than this, depending upon the material involved and the system parameters, a more straightforward solution involves the initial emplacement of a thin plastic bag or balloon; this is partly filled with water or oil or other cushioning liquid and the pile gently and slowly built by positioning the explosive pieces; the liquid is pumped out after the pile is constructed, and drainage and drying(as by warm air circulation) put into effect. The dry explosive pile is now ready for detonation (firing means have already been placed therein, as by waterproof squibs and surface-communicating electric firing ca-

bles), with or without removal of the encasement; gentle cutting can be used to remove the plastic envelope, or it can be merely dropped over and around the explosive pile to the floor of the firing vault.

When high detonation and large gas volume production(as to contribute to the production of shock light) is desired, Astrolite-G(not "astralite") can be employed. Astrolite-G is a clear liquid explosive especially designed to produce a very high detonation velocity(8200 meters per second). It is 40 times less sensitive to impact shock and antibatic compression than nitroglycerine and four times safer than nitromethane, characterized by high energy release and very high gas release. Astrolite-G can be sorbed onto porose substrates for ease of handling, for reduction of density (in terms of explosive material), and for the production of physicochemical systems in which the sorptive material may enter into the optoexplosion to alter the balance between kinetic and optical energies.

Astrolite-A, a solid, and Astrolite-P, a plastic explosive are both tractable to the fashioning of explosive masses of an interstitial nature, e.g., foamed solid explosives and explosive fabrics, just described.

Furthermore, Astrolite-P can be used as a "liner" or "lens" charge in the firing chamber of the system, as for example layering the surface of the concave rear of the explosion leg.

Binary, ternary or other multisubstance explosive ingredient preparations may initially be in admixture(as in the case of aluminized explosives, or the baronal-type compositions), or they may be separated and then brought intimate relationship with a resulting explosion(as in the case of hypergolics).

Hypergolic optoexplosives were set forth in the original disclsoure and further detail is not necessary here, except to add that useful classes of compounds fall into the groups comprising metal(usually aluminum) alkyls, MR_3(M = metal, R = alkyl); metal alkyl halides, MRX_2(R = halogen, usually iodine) and metal dialkyl halides, MR_2X; and metal alkyl hydrides, $M_2H_2R_4$, like aluminum tetramethyl hydride, which undergoes explosive combustion with oxygen or air with the release of violet light. Air, oxygen, chlorine, fluorine and other gases are usually the second reactant in driving the system into optoexplosion.

Dust explosions, i.e., particulates usually metal reacting with an atmosphere like oxygen(with firing means), comprise a versatile binary optoexplosive light source characterized as capable in the present improvement of supplying optical energy in a sequence of bursts, enabling repititious shots when FRO feed is employed. A basis for this is set out in my U.S. Pat. No. 3,309,620. Thus, the reactants are fed separately into the firing chamber by pipe from a source at say ground surface, with say electric ignition means being employed to induce the dust explosion. In order to sustain a dispersion of solid particles in the gaseous reactant medium, bottom and/or side up-jet(s) of particulate reactant and/or gas reactant can be utilized; slit deagregators and ancillary means can be employed in such a system. Various dust cloud generators are summarized by D.J. Seery and H.B. Palmer("The Combustion of Dust Clouds: A Survey of the Literature", Coal Research Board, Dept. Fuel Tech., College of Mineral Ind., The Pennsylvania State Univ., Special Research Rept. No. SR-17, 30 pp.(28 refs.), Nov. 30, 1959).

The theory and applications of dust cloud explosions are set out by Seery and Palmer, cited supra; and for further information in the practice of this modification of the present invention the artizan is referred to: "-Handbook on Aerosols," Washington, D.C., U.S. Atomic Energy Commission, 1950; J. Dalavalle, "-Micrometrics", New York, Pitman Pub. Co., 1948; "Third Symposium on Combustion and Flame and Explosion Phenomena", Baltimore, Ma., Williams and Williams Co., 1949; Ibid., "Sixth Symposium on Combustion", New York, N.Y., Reinhold Pub. Co., 1957; H. Green and W. R. Lane, "Particulate Clouds", London, Spon Publishers, 1957.

In connection with the area of metal dust explosions, I would especially refer to the abundant literature generated out of the activities of the Hartmann Group, Dust and Explosions and Mine Experiments Branch, Explosives and Physical Sciences Division; U.S. Bureau of Mines, Pittsburgh, Pa., wherein a great deal of data are set forth on the numerous facets of the subject; also, cf:-S. Haffner, "A Survey of Available Literature on the Rapid Combustion of Metals in Air," 18 pp., PATR 2061, Picatinny Arsenal, Dover, N.J., September 1954, AD 44,543(25 refs.), which paper also sets out data on the flashtimes and relative outputs of various metals and alloys and binary nitrated and chlorated metal (Al, Mg, Al—Mg, Zr, Al—Li, Al—Ti, Al—Mg—Zr) formulations.

Of distinct interest in connection with the subject of chemical optoexplosives is the work of I. Hartmann, J. Nagy, and M. Jacobson("Explosive Characteristics of Titanium, Zirconium, Thorium, Uranium and Their Hydrides," 16 pp., U.S. Bureau of Mines, Rept. of Investigations 4835, December 1951), wherein there is set out data on the explosive behaviors of these elements and their hydrides in such atmospheres as pure oxygen, nitrogen, carbon dioxide, helium, and argon, the latter four in various mixtures with oxygen.

It is not deemed necessary to detail this subject herein, other than to reiterate my critique given at the outset of the present section, wherein optical assay of the dust explosion phenomenon has not been monitored in the many studies in this field because of the tilt to blast phenomena. Reference is made to my patent cited supra on the optoexplosive facet of reactaions of various metal particulates with different atmospheres, including those of air, oxygen, nitrous oxide, nitrogen, and carbon dioxide. The gaps extant in dispersed metal and metalloid reactant,and gas and vapor reactant, species are quite large, with blast predominant and light nugatory. For example, the ignition and combustion of powdered metals(Al, Li, Be, B, Ca, Ce, Ti, Zr, Th, U, Mg) are reported for the atmospheres of earth, Mars(2.16 percent Ar, 11.21 percent CO_2, and the balance N_2), and Venus(4.10 percent Ar, 9.17 percent N_2, and the remainder CO_2)—the latter two being simulant atmospheres—by R.A. Rhein(Astronautica Acta, 11 (5), 1965). These data may be of interest to the artizan in designing metal dust opto-explosive light sources and systems.

An example of a large class of binary optoexplosives is what I call the "baronal-type." These are thermochemically designed or formulated out of empirical test batches, as may be necessary, and may be represented by:

$mA_x(B)_y:nC:oD$

where:

A = a cation portion of the molecule $A_x(B)_y$, which is usually alkaline earth or metal;

B = an anion portion of the molecule, such as nitrate, chlorate, perchlorate, bromate, iodate or other available oxygen anion or oxidizing moiety;

C = a particulate metal, such as Al, Zr, Hf, Mg;

D = an optional explosive to assist in chemically driving the reaction between $A_x(B)_y$ and C;

x and y = the valences of the anion and cation, respecyively;

m and n(also the optional o) = the mole proportions or weights of the ingredients.

Cation A is preferably one of the 19 elements in the table of R. K. Landshoff et al. (cited herein) which lists the states and spectra of monoxides, covering the spectrum between the ultraviolet and the far infrared, although I do not exclude others in the periodic table. In addition to monoxide and like spectra, the kinetics of baronal-type reactions also involve emission by neutral and ionized A species, the spectral data for which can be found in the standard handbooks.

A typical baronal-type optoexplosive is made of barium or magnesium nitrate and aluminum or zirconium powder in say 60:40 proportions; TNT, PETN, RDX, up to say 10 parts, can be added to enhance the detonation reaction and lift the reaction rate. A similar system studied by J.M. Gerhauser(cf. Ordnance, July-August 1967, pp. 1-2(article by W.W. Cavell et al.)) on the flame temperatures of metals(Mg, Al, Li, Ca, Ni, Ti, Bi, B, V, Mo, Cr, Mn, Zr, Hf) under oxidizing conditions established the brightness of a reaction, in addition to being a function of high flame temperature, as dependent upon the boiling point of the oxide and the solubility of the metal in its oxide.

Ternary and quaternary compositions may be exemplified by the foregoing working formula wherein $A_x(B)_y$ comprises two compounds, the cations of which may be the same of dissimilar and the anions of which are dissimilar when the cations are the same, as for example alkali metal chlorate and metal nitrate. Likewise, C may include two or more metal particulates and, in addition to the metals just listed, I especially point to particulate rare earth metals.

My broad designation by the foregoing formula for the baronal-type optoexplosives, therefore, gives a galaxy of agents of greatly widened scope insofar as choice of ingredients is concerned. When thermodynamic modeling is feasible(and it is not always available because of lack of thermodynamic data on substances of potential interest), such formulations are tractable to reduction by computer.

Certain metallic compounds, particularly metal-organic compounds, are a preferred class of optoexplosives. These include picrates, azides, fulminates, amides, and various double compounds. (Substances like chlorine azide, ClN_3, while not considered here are not excluded from the scope of this improvement; ClN_3 explodes with an emission from the ultraviolet(UV) to the red, intense in UV and blue, and peaking at 5000 to 5500A).

The explosive rearrangement of metal-organic molecules like the azide group bound to metallic cations known to be unique for spectral emission properties is an example. Thallium azide, TlN_3, explodes with a pronounced green flash(Tl(neutral atom) emits persistent lines at 5350.4(strongest), 3775.7, 3519.2, and 3229.7A; singly ionized Tl emits its strongest line at 1908.6A). The explosion spectra of the azides of Ca, Sr, and Ba show not only the triplet system but also lines of the singlet system. Zinc azide, $Zn(N_3)_2$, emits only triplet lines of the diffuse and sharp series. Oxide bands are also present in these spectra(cf. A. Petrikaln, Zeit. phys., 37, 610-618(1926); Chem. Abs., 20, 2791(1926)). The explosion spectra of various substances has been recorded by H. Muraour and A. Michel-Levy, Mem. Artillerie Francaise (Paris), 21, 263-270(1947). R.K. Landshoff et al.(cited herein) has tabulated the states and spectra of the following monoxides: Al, Be, Bi, Ca, Ce, Cu, Cr, Fe, La, Mg, Mn, Ni, Sc, Sn, Ta, Ti, V, W, and Zr; these data should be consulted in the workup of spectral data for the corresponding azides.

Because of the highly tempermental nature of certain metal-organic optoexplosives like the azides exceptional precautions must be taken in the preparation, refinement and handling of the substantial amounts which may be used in an optoexplosive light generator. It goes without saying that the artizan should very thoroughly acquaint himself with all aspects of the knowledge about a particular metal-organic optoexplosive, and should make scaled-down runs before attempting a full-sized shot made say from the piling of dry or semi-dry(preferably thinly coated with conductive polymer so as to prevent electrostatic charge build-up and detonation) bricks or briquettes. Reference should be made to Basil T. Federoff, et al., "Encyclopedia of Explosives and Related Items," vol. I, pp. A520-A73, CFSTI AD 257, 189, Picatinny Arsenal, Dover, New Jersey(1960), 691 pp., for information and extensive documentation of the inorganic and organic azides, azo compounds, and the like; also, H. Rosenwasser, "Hydrazoic Acid and the Metal Azides(A Literature Survey)," Rept. 1551-TR, 28 October 1958, USA Engineer and Development Laboratories, Fort Belvoir, Virginia, AD 208,892(437 references to the literature).

Metal-organics like the azides are extremely sensitive to friction and shock, so extraordinary and special precautions and measures must be used in the large-mass loading of an optoexplosive system. This loading is done by emplacement of a water slurry in situ, with subsequent drying or dewatering to bring the mass to the state necessary for the explosion. Among the various means which can be used are the following:

a. Pumping the azide or other slurry into the firing chamber of the explosion leg of the system, allowing the water to drain by gravity and other natural means, with a final gentle drying by circulating warm air over the mass;

b. Pumping the explosive slurry onto a horizontal pallet or tray, allowing the water to drain and evaporate, and then cautiously bringing the pallet up to or near vertical position, with a final drying by circulating warm air; a small amount of water-soluble binder such as methyl cellulose or polyvinyl alcohol is added to the slurry to keep the mass from crmbling; like (a), supra, this procedure can

be carried out within a large, thin, transparent plastic bag first emplaced in the firing cavity, its bottom having drain holes;

c. As of (a) or (b), above, with internal warming means provided by circulating hot water pipes or by low-temperature pyrotechnic heater pipes, both embedded in the explosive mass, so as to drive off the undrained water at a slow rate and bring the optoexplosive to the required state of dryness;

d. Similarly to (b) and (c), supra, when an enclosure is utilized adjacent water-sorptive(e.g., silica gel) means for dry-out. Should there by compartmentalization(e.g., a backing cell to the pallet or tray) chemical desiccant like P_2O_5 can be employed(suitably chosen desiccants might also serve as brightness and temperature modifying dopants in the subsequent explosion);

e. The use of freeze-drying and soil dewatering techniques well known in the chemical process industries and in engineering, as for special applications or problem of handling and loading.

The sensitivity of the azides, like the fulminates, styphnates, and the like, can be reduced by leaving residual water and by dextrinating. The detonation velocities of these explosives depends, like most explosives, upon the density, so detonation velocity is generally on the low side of the values given in the literature, if not much less, e.g., about 4000 meters per second for lead azide, and about the same value for silver azide. For lead styphnate the value is approximately 5000 meters per second; and for copper chlorotetrazole the value is evidently not reported. Metal halotetrazoles, metal 2,4-dinitroresorcinates, and metal 4,6 dinitroresorcinol basics are included in the foregoing category. These and like substances may be preferable to the because of their lessened sensitivities which make for easier handling.

The tellurian optoexplosive light generator, in particular, is peculiarly suited for the use of chemical combinations, detonable or hypergolic, which are difficult to work with because of handling hazards, toxicity, and like factors. And especially when large masses of reactants must be manipulated for optoexplosive light generation, as for example between several hundred pounds and several tons or more. The oxidative optoexplosion of cyanogen(C_2N_2), using oxygen, nitrous oxide, or other suitable oxidant is an example of a reaction having a brightness temperature ranging between 6000° and 8000°K. This reaction, as desired, can be doped so as to raise the color or brightness temperature. For example, an excess of carbon particles or of carbon in the stoichiometric or other reactant ratios; or of including very high surface area metals(e.g., rare earths, alkali, transition elements); or of including(e.g., as explosion leg filler) such gases as those of the inert family of He, Ar, Kr, Ne, Xe, or of other gases selected out of consideration of quantum mechanics and their behavior under excitation.

A large amount of work on cyanogen and other related compounds of the carbon, nitrogen, and oxygen system has been carried out by the A. V. Grosse group at Temple University, wherein flame temperatures between approximately 5000° and 6000°K were obtained, at pressures ranging between atmospheric and 40.82 atmospheres(600 psi). High temperatures are obtained from certain of the compounds of the N:C.(C:C)$_n$·C:N series reacted with oxygen, including gaseous (C_4N_2) and others.

Typically, the investigations of the John L. Wright group (as reported in Volume II of "Army Science Conference Proceedings," pp. 539–552, 14–17 June 1966(AD 634,616; the Wright paper per se is AD 634,655) set out light pulse data from cyanogen-oxidant combinations, particularly detonations sparked or squibbed at atmospheric pressure. I note that these studies establish feasibility and proof-out my U.S. Pat. No. 3,309,620, titled "Method and Apparatus for Pumping a Laser by Exploding Dispersed Metal Particles," filed Mar. 23, 1963, and granted Mar. 14, 1967. This, in turn, concerns optoexplosive sources utilizing metal or other particulates, as described elsewhere herein, as well as in the parent disclosure.

Thus in the reaction

$$C_2N_2 + O_2 \rightarrow 2CO + N_2$$

high adiabatic flame temperatures are produced, the maximum theoretical temperature being 6200°K for 50:50 mixtures at atmospheric pressure(rising to 57 atmospheres pressure upon detonation). Detonation velocities are in the range of 2700 meters per second. The detonation time(i.e., the light pulse life) ranges between 50 and about 200 microseconds. Brightness temperature is increased by doping with an excess of carbon, and temperatures in the vicinity of 8000°K are attained by admixture of small amounts of such dopants as Ar, He, and Xe.

Illustratively, in this improvement I prefer to use the cyanogen reaction on a larger, pressurized scale. Thus, the cyanogen and the oxygen can be moderately presurized into a double balloon provided with suitable detonators. Balloon container materials include clear tetrafluoroethylene elastomer (Teflon) of the like. The balloon container is filled immediately before the explosion, each compartment having an inlet pipe. The disadvantage of the presurized balloon system is, of course, the limitation placed on the mass of reactants; however, for relatively small, low energy optoexplosive systems this is an advantage a sequence of runs is desired and destruction or injury to the firing leg is to be avoided(e.g., caving).

Alternatively, for high energy systems I prefer the use of (a) large masses(e.g., several tons or more) of reactants, (b) under pressure(usually liquified or, if not, in a suitable combination of dewars or cryostats which are separately vented to the surface of the ground) which are (c) implosively combined to give the optoexplosion. Admixture or commingling of the reactants isolated from one another in a compartmented container or two adjacent, fitted containers can be forced by low order explosion, including shaped charge means. The resulting optoexplosion may be symmetric or asymmetric, depending upon the form of the contained, reacting masses, and upon whether or not a directed energy explosion is used for their blending. As desired, part or all of the container may serve as dopant(e.g., when coated with dopant), to raise the brightness temperature.

Cyanogen is liquid below 34.4°C; it is soluble in water, ethanol and diethyl ether. Above 500°C cyanogen forms a solid, paracyanogen, $(CN)_n$, a sub-

stance of potential as a reactant. The oxidants may be several, as for example liquid air, liquid oxygen(with or without carbon(a commercial explosive known in that art)), liquid ozone(liquified at approximately − 193°C, obtained as a blue liquid by supercooling ozonized air), and liquid or pressurized nitrous oxide, N_2O(−90.8°C).

For highly pressurized reactants, supra, which are to be explosively blended, a convenient container is that of biconical geometry, with the cone bases in apposition(i.e., diameter largest at the girdle), and with a frangible wall separating the two conical chambers. At each end is placed a shaped or other explosive charge, the two detonated simultaneously. When of the gas-bottle type of pressure container, middle and side wall strengths should be such that they are ruptured. When of the dewar-type each compartment is provided with inlet pipes for filling, and with separated, outlet pipes for venting.

For the aid of those in the art the following literature relates to cyanogen reactions and the kinetics thereof: H.E. Williams, "Cyanogen Compounds: Their Chemistry, Detection and Estimation," London, Arnold & Co., 1947; V. Migrdichian, "The Chemistry of Organic Cyanogen Compounds," New York, Reinhold, 1947(Amer. Chem. Soc. Mon. No. 105); H. James et al., Compt. rend., 236, 811–813(1953); H. James and P. Lafitte, Fifth Symposium on Combustion, Pittsburgh, Pa.(US), pp. 616–619 (1954); Basil T. Federoff, "Enclyclodepia of Explosives and Related Items," vol. III, Picatinny Arsenal Tech. Rept. 2700, Picatinny Arsenal, Dover, New Jersey(USA) 1966(cf. pp. C-586 to C-588, wherein such compounds as cyanogen bromide, cyanogen chloride, cyanogen fluoride, cyanogen iodide, and others are described); A.V. Grosse and C.S. Stokes, "Study of Ultra High Temperatures," (Temple University Research Institute, Philadelphia, Pa.), U.S. Dept. Commerce, OTS Rept. PB-161,460, 26 pp. (1960).

When, as for example using a CX source **10*d*** in FIG. 5, **10*d*** is a cylindrical mass aligned so that its long axis is parallel to **76**, as is detonated at the butt end, the resulting explosion is "quasi-asymmetric"–for the direction of the light output is not perpendicular to the axis, but is inclined in a direction opposite to that of the detonator. In the case of FIG. 4, where **10*c*** carries the detonator at its center and say mid-way along the cylinder, the same thing obtains, except that the explosion energy issue is bilateral in the direction of **64** and **74**(or **56** and **66**, as the case may be).

These cylindrical explosions, as they are termed in the art, have for example been investigated by R. Collins("Some Methods of Generating Cylindrical Explosions," Univ. of Toronto, Institute of Aerophysics, UTIA Tech. Note 43(1960). Solid, liquid and gas-mixture explosive compositions exhibit cylindrical explosions phenomena. Features such as the main shock wave, contact front, and imploding second shock wave are present in these explosions.

The cylindrical explosion is particularly suited for use in optoexplosive systems where directed-energy explosions are desired, e.g., directed into the shock-sink; also, where gas and liquid explosives are employed in repetition shooting when system integrity is to be maintained.

The cruciform luminsoty phenomenon is an explosive effect highly adapted to asymmetric energy release, particularly in the case of multilegged optoexplosive light generators. When a cube of explosive is detonated the resulting explosion takes the form of an optical cruciform having its legs in directions perpendicular to the faces of the cube, with a dark zone all around the crucifix(called the "dead zone" or "zone morte").

Therefore, in FIG. 4 for example, when source **10*c*** is a cube or rectangle, energy will be directed into legs **56** and **66**(with, of course, corresponding lateral emission). Should FIG. 4 take the form of a Y, then a prism of explosive is employed, each face of the prism facing into each of the light-legs and thence into the shock-sink legs. Should FIG. 4 take the form of a crucifix, with four legs, then the cube of explosive is arranged so that each of the faces corresponds to each of the legs. Likewise, should FIG. 4 be of what I have previosly called "spider-leg" configuration, i.e., of many branching legs, then a polygonal mass of explosive is utilized, the number of faces corresponding to the number of legs.

For additional information on the theory and mechanics of the cruciform luminosity phenomenon and like asymmetric effects, the artizan is referred to: E. Burlot, Mem. Artillerie Francaise(Paris), 9, 789–957(1930); P. Demougin, ibid., 9, 961–972 (1930); H. Ahrens, Zeit. gesamte Schiess- under Sprenstoffwesen-Nitrocellulose(presently Explosivstoffe(Munchen)), 38, 175–177 (1943); H. Muraour, Compt. rend., 222, 1108(1946); A. Michel-Levy, ibid., 223, 62 (1946); D. Riabouchinsky, ibid., 237, 222–224(1953); also, the Federoff tomes cited herein(vol. III, C563–C564(1966)).

The shaped-charge can be fabricated in the usual manner from explosive material of desired detonation rate(cf. the table given previously herein). For extra-large shaped-charges, or those of special configuration, where casting or conventional methods are difficult or not feasible, the technique I have devised(and tested using dynamite powder between two sheets of heavy paper) may be useful: Namely, an asymmetric charge rolled into shape from a flat sheet. Detasheet flexible explosive(= PETN(ca. 85 percent + elastomer binder), having a detonation velocity of the order of 7200 meters per second, is first cut into a right-angle triangle. This triangular sheet is then truncated by cutting off both of the acute angle ends, the truncation of each being decided by the length of cone-apex-to-base and the overall diameter of the final product desired; the angle of the cone is determined by the angle of the greater of the two acute angles; the length of cone-apex-to-base is the truncated length at the lesser of the two acute angles. The sheet thus cut is then rolled back onto itself, beginning with the truncation at the lesser angle, with a cylinder having a coned face being the result. As desired, dopant metal(Al, Zr, rare earth), carbon or the like may be rolled into the shaped charge formed in this way. Cement may be applied to the surface just before rolling, or the cylinder may be tied. Detonation, with or without booster, at the base is done in the usual way.

Illuminating flash and flare and light-signaling compositions are chemically designed as light producing

media(involving not only the visible but also the ultraviolet and/or the infrared). By nature these are considered as burning or deflagrating, as contrasted to explosive in their behavior. However, when highly confined so as to permit pressure buildup, most of these agents become explosive, producing a shock along with the light output.

In this improvement I employ as a CX light-emitting source an otherwise pyrotechnic and deflagrating composition, as desired. Instead of container confinement I prefer implosion confinement of the pyrotechnic material. Thus, the pyrotechnic may be a component in an optoexplosive system which comprises a mass of that pyrotechnic having mild implosion means, e.g., one or more hemispheric hollow charges, enveloping the pyrotechnic. These shaped charges act as the confining "container", allowing pressure build-up and resulting explosion of the light-emitter. The explosion "container(s)' may be of any suitable size and configuration, and of explosive well known in the art; the implosion sheaths or envelopes are squibbed and detonated in the usual manner, e.g., as by electric firing.

Alternatively, explosive pressurization or compaction can be used upon an otherwise deflagrating, light-emitting composition(or other suitable compositions or substances, described below) so as to induce an optoexplosion in that composition. This includes the simple expedient of sandwiching a layer of the composition between two steel plates (making a flat sandwich when the plates are parallel, or a wedge-shaped sandwich when they are angular to one another). The top plate carries a slab of explosive, which upon detonation causes the explosive pressurization and compaction. The light is released from the edge of such a sandwich, so the ensemble should be aligned accordingly in the optoexplosive system. Other, more elaborate and sophisticated arrangements of this kind can follow the techniques employed for explosive-cladding and forming of metals. In this and like instances there is a layer of light-generating reactant which undergoes high-rate and high-force pressure effects between a slapper and an anvil.

So that enhanced light-releasing area is obtained such an ensemble may comprise a core of driving explosive within a slapper tube which is made up of two, three or four "petal" members (which move outwardly in the discoid or doughnut arrangement upon explosion of the core). The petal members, in turn, are surrounded by a ring of the optoexplosive composition and this, in turn, is rimmed by an outer hoop of high-strength steel which makes up the anvil. This explosive disc ensemble is characterized by a greater light-emitting area, and may be of any desired diameter and thickness.

When greater explosive forces are required for the pressurization and compaction process what I call an "implosion doughnut" can be utilized. Illustratively, this is a doughnut ring or a segment of same (e.g., of an anchor ring or torus) of square, rectangular or circular cross-section; the ring or segment thereof may be formed as a single piece or may be assembled from a series of segments. The inside surface of the ring is grooved, e.g., having a V-shaped or U-shaped or like groove, and the peripheral edge is provided with a series of detonators, it is seen that a "shaped implosion charge" is the result. The ring may be of cast explosive, pressed explosive, or molded explosive composition characterized as having a high detonation velocity (e.g., TNT, RDX, PETN, Astrolite(not the "astralite" of the earlier explosives art) compounded into a settable preparation with suitable cement or binder, and the like).

The hole of the implosion doughnut is filled with the chemical or nuclear(as for low-grade explosions; cf. my discussion hereinafter on this subject) explosive reactant. Simultaneous firing of the detonators(with detonation of a booster ring which may be present) results in an implosion which rises to a pressure peak and then quickly drops off as the reactant undergoes reaction and escapes from the face of the doughnut. Such an implosion doughnut may or may not be backed by a contact wall of high-strength metal or very hard rock, as desired. When light-release from the hole filler is desired from both sides such backing of course is not used(e.g., as 10c in FIG. 4).

Illustratively, the reaction of

$$Ca(NO_3)_2 \cdot 4H_2O + 5Ca \rightarrow 6CaO + N_2 + 4H_2O$$

with 46% Ca and 54% $Ca(NO_3)_2 \cdot 4H_2O$ proceeds in a typical deflagration, with a theoretical energy output of 1.45 Kcal/gm.

However, when this afore-mentioned mixture of calcium and hydrated calcium nitrate is pressurized to approximately 14×10^3 psi, an explosion occurs. At this order-of-magnitude pressure or greater, as may be produced by implosion confinement, I consider that the light-emitting species are not the same as those of the simple deflagration. Thus, a portion of the light emitted in the optoexplosive reaction can be considered derived from $CaO(^1\Sigma)$:

State	Energy	F.S.	System	v'	v''	Wave lengths (A)
$A^1\Sigma$	0.94	X	Red	5	3	9229–7308
B^1H	3.2	X	Blue	-	-	4519–3373
$C^1\Sigma$	3.6	X	UV	-	-	3753–3287
?	-	-	Far IR	-	-	10533–9133

(Notes: (a)Light generation together with the deflagration behavior of the $Ca + Ca(NO_3)_2 \cdot 4H_2O$ system is set out by R.M. Blunt, "Evaluation of Processes Occurring in Pyrotechnic Flames," Denver Research Institute, Denver, Colorado, RDTR No. 91(AD 655,820), 75 pp. (cf. pp. 4–5), 15 March 1957, including magnesium and calcium species spectra, and a resume of the important papers since about 1920 on sodium spectra (see dopants herein). (b) In the aforementioned data for the CaO molecule and its ground state and higher energies are first given, with the initial and final states of the transition given by the system; v' and v'' are the maximum and initial and final vibrational transitions; wavelengths refer to those of the transition, according to the best data I have at hand (Table of the States and Spectra of the Monoxides, p. 290–295, in DASA 1917–4, "Thermal Radiation Phenomena," volume 4, "Excitation and Non-Equilibrium Phenomena in Air," by R. K. Landshoff and J.L. Magee, Lockheed Missiles

and Space Company, Sunnyvale, California, November 1967(AD 664,496)).

It is not practicable here to go into detail on pyrotechnics, especially as it relates to flare, flash, illuminating and like preparations. Suffice to say, however, that the foregoing example illustrates the domain of explosively or implosively confined light-generating chemicals.

In this connection I would especially point to those pyrotechnic and deflagratable compositions set forth in my U.S. Pat. No. 2,995,526(filed July 27, 1951 and granted Aug. 8, 1961), wherein some 600 varieties of preparations including about 60 different elements are disclosed. Although originally intended as smoke-forming munitions, these pyrotechnic compositions, upon implosive reaction—especially with an excess of fuel and/or oxidant to raise the reaction temperature—offer a large number and wide variety of light emitters. Thus, since my tests and studies from about 1950, with an intensive following of the literature on pyrotechnology, there has been a paucity of information on preparations containing oxygenated and peroxygenated halides other than chlorine. As for example, bromates, iodates, and perfluorinated compounds, both organic and inorganic.

There is an abundant literature on light-creating pyrotechnics, and the artizan is referred to the following examples: A.A. Shidlovsky, "Fundamentals of Pyrotechnics," 3d. edition, Tech. Memorandum 1615, translated by U.S. Joint Publication Service from "Osnovy Pirotekhniki" (1964), May 1965, 414 pp. + 308 references, AD 462,474; Duane M. Johnson, "Proposed Kinetics and Mechanics of Illuminant Flares: Maxi-mizing Efficiency," U.S. Naval Ammunittion Depot, Crane, Indiana, 13 January 1966, 40 pp. + 6 references("...the best combination of chemicals for illuminant flare compositions has continued to be a fuel-rich mixture of magnesium and sodium nitrate. Unfortunately, very little information is available to explain the reason why this type of composition gives the best illumination efficiency.")(AD 627,649); John E. Wildrige, "Experimental High Intensity Flare Systems; Design and Tests of," ibid. August 1966, 111 pp.(AD 638,490); J.N. Gerhauser, "Spectral Emissivity of Flash Combustion Reaction Study Program(Final Technical Report)," North American Aviation, Inc., Los Angeles, California, 1 June 1963 to 31 May 1964, 152 pp.(AD 443,158); Paul Tavernier, "Contribution to the Study of Flash Powders," Tech. Memorandum No. 1082, by U.S. Joint Publication Research Service (October 1963) from The Laboratoire De La Commission Des Substances Explosives, 17 May 1944(AD 42,446); Basil T. Federoff, et al., "Encyclopedia of Explosives and Related Items,"(vol. I. 1960(AD 257, 189);vol. II, 1962(AD 422,747); vol. III, 1966(AD 653,029)), Picatinny Arsenal, Dover, New Jersey(USA); Ibid., "German Section," 1958(AD 160,636), PATR 2510; and, of course, the usual books and periodicals on explosives and the like.

Encapsulants(or microencapsulants when on small scale) can be made free-flowing, after the manner of dry powders, even though they contain liquid cores; thus, liquids can be handled as if they were solids, volatile materials and reactive compounds retained and then released under selected conditions, and sensitive materials susceptible to moisture or oxidation preserved until needed. By varying the wall thickness and mass a time-delayed release can be had. And by varying the nature of the wall material that material can contribute to chemical reaction, e.g., as a fuel. Microencapsulated moieties can be produced over a wide range of temperatures involving a wide range of atmospheres, e.g., formed within inert gas atmospheres when highly reactive substances are encapsulated. While the wall material of the coacervated product is most often organic, it may also be a specialty substance like fluorinated polymer or silicone or metal imidazole.

Many substances alone flare in combination are uniquely interesting as optoexplosives, but are not ordinarily practicable because of instability singly or ultraviolet multibase mixture, sensitivity to low-order kinetic forces, volatility, extreme chemical reactivity, and the contrasted The literature is, in fact, filled with examples of this kind of material—not used because of the various working obstacles they present. I prefer to overcome these obstacles by isolation of the substances, typically by microencapsulating the various ingredients and then by combining these into the final polyphasic product.

Briefly, the art of microencapsulation—dating back some 30 or more years—embraces the conversion of two-phase systems into one-phase by encapsulating the reactive ingredient(s) to block their activity until such time as they are required for use. Microencapsulation involves the formation of small spheric bodies, usually between several microns and upwards of a centimeter in diameter, comprising a wall or envelope enclosing the active medium of gas, liquid or solid, generally the latter two states. The envelope is most often a polymeric substances like gelatin, polyvinyl alcohol or the like, which may be reinforced by additive and/or hardened by subsequent chemical treatment.

Thus, optoexplosives or optoexplosive ingredients which cannot be worked alone or, especially, handled in the large amounts which may be required for certain versions of the present invention, microencapsulation is frequently the answer; the following substances, liquids and solids, are usually compliant to this approach, illustratively including for purposes of this disclosure:

i. highly reactive substances characterized by an exceedingly high surface area, as for example particulate, dust and filament solids like colloided metal powders and pyrohphorics;

ii. alkali and alkaline earth metals, including alloys thereof;

iii. peroxy compounds, particularly peroxy organics and peroxyacids;

iv. reactive allotropes like white (or yellow) phosphorous;

v. fuel-oxidizer type multibase compositions wherein incompatibility precludes use, especially on a large scale (a study of the literature on propellent double-base and multibase candidates that have been excluded because of explosive or other dangerous qualities provides a very good guideline, and the same is true for the same reason for rejects in the deflagratives and pyrotechnics art(e.g., flare, flash, smoke, and like munitions);

vi. ozone, fluorine and like enriched agents such as solutions and sorptives; also, ozonides, which are notoriously difficult to handle;

vii. interhalogen compounds like chlorine monofluoride, ClF; chlorine trifluoride, ClF_3; iodine pentafluoride, IF_5; bromine pentafluoride, BrF_5; bromine trifluoride, BrF_3; and the like;

viii. oxyhalogen compounds like chlorine heptoxide, Cl_2O_7chlorine monoxide, Cl_2O; chlorine dioxide, ClO_2; fluorine nitrate, NO_3F; so-called fluorine perchlorate (chlorine tetroxyfluoride), $ECIO_4$; perchloryl fluoride, $ClFO_3$; and the like.

A further advantage of microencapsulated explosives is the cushioning provided by both the resilient wall member and the matrix gas, if any, or the matrix liquid (which may be reactant, as desired), to protect the sensitive material from insult. Note is made of the fact that the wall of the encapsulant body can be electrically-conductive, as may be the case with the encapsulant environmental medium, to prevent build-up of electrostatic charges.

Encapsulated substances—herein generally designated as microencapsulated—of the optoexplosion modifier kind are mentioned elsewhere in this disclosure.

NUCLEAR OPTOEXPLOSIVES

From an applications standpoint the blast energy of an NX device has dominated the art. Materials treatment by NX blast is exemplified by the PLOWSHARE program of the United States, involving nuclear mining engineering and excavation. Penetrating electromagnetic and particulate radiations uses are usually of secondary role, as in tellurian transuranium isotope studies. Sundry proposals and investigations embrace the thermal effects of NX energy on mineral values in situ. Information on the status of the subject can be found in "Major Activities in the Atomic Energy Programs," January-December 1967, 397 pp., U.S. Atomic Energy Commission, Washington, D.C., 1968(U.S. Government Printing Office).

A varying and often substantial portion of the energy released in the explosion of an NX device is optical energy, depending upon the yield, nature and design of that device, and depending upon the environment in which it is exploded. Except for direct conversion to heat by absorption in a material, the optical energy per se and substantially freed of blast and shock and explosion debris, and penetrating and particulate radiations, has not been hitherto available, let alone used, in the case of close-in NX explosions(e.g., explosions typified by distances from the shot where blast and non-optical radiations are overwhelming by their magnitude).

In this invention I extract and isolate the light per se of a close-in NX explosion and, as desired, manipulate it in one or more of several ways; for example:

a. When the raw light is extracted from a nuclear explosion free of extraneous energies, I call this "clean atomic light" and designate it by the acronym "CAL"; a CAL beam can be impacted upon an irradiable target to produce photophysical or photochemical changes therein, for example;

b. Under ordinary circumstances an NX device-powered tellurian optoexplosive system produces a CAL beam of round or circular cross-section with a face area which may vary between several and several hundred square feet. However, when the CAL beam is passed through aperture means of desired configuration the resulting CAL beam is changed into what I call a "shaped atomic light" or "SAL" beam. One utility of the SAL beam is that it can be made to correspond to the profile of a near or far target, consistent of course with ancillary optics which may be included in the fashioning of the beam and consistent with the inverse square law; additionally, the limitations placed by the inverse square law can be overcome by use of a flux redistributor system(described hereinafter);

c. Without further manipulation the CAL or SAL beams will generally have a more or less uniform energy density across the face at a given point; however, by suitable treatment, e.g., selected portions of the beam given reflection or reflection-diffraction pass through a flux redistributor(cf. FIG. 5), the energy density at a given point may be made to vary within that beam, as for example a longitudinally bisected CAL or SAL beam of halves of different fluxes;

d. By means of a multilegged system(as in FIG. 4), two or more CAL or SAL beams can be fashioned so that each is of different spectral qualities, as for example two invisible beams one of which peaks in the ultraviolet and the other of which peaks in the infrared; this is accomplished by the use of FRO means in the legs, each of appropriate and different optical behaviors; in turn, these two or more beams can be worked together;

e. Following from (c) and (d), supra, multiple and/or longitudinally multisected beams may be spectrally different;

f. An additional working of the two or more beams results from either the superposing or sequencing of sinusoid light bits obtained from timed-life FRO means of different lives;

With the target including suitable optics, as for example a train of imaging reflectors, the aforementioned arbitrary, working distinctions for the light enable mixing, non-linear working, or other optical treatment. In effect, then, by changing the design and performance parameters of this as well as the parent invention there may be obtained an explosion-produced light beam characterized by:

1. Time (or integrated energy)-modulation;
2. Frequency(or wavelength)-modulation;
3. Intensity-modulation;
4. Combination of these.

While I have just described the fashioning, working and manipulation of optoexplosively-derived light within a nuclear source framework, it is evident that what I have stated holds equally for the light emitted by chemical optoexplosives.

As to the characteristics of NX energy sources, these have been published in such sources as: W.J. Frank, "The Characteristics of Nuclear Explosives," (pp. 65–68 of the Third Plowshare Symposium Proceedings, 1964, cited herein); also, S. Glasstone(ed.), "The Effects of Nuclear Weapons," rev. ed., U.S. Atomic Energy Commission, Washington, D.C., 1964, which also sets forth literature references of interest to the artizan.

A nuclear reaction under explosive or implosive confinement produces enormous energies for the mass and volume of the materials involved. NX sources may range down to 1 to 2 T in yield, and of course upwards by a factor of 10^3(KT) or 10^6 (MT). The traditional unit for measuring NX explosive energy is the kiloton(10^3 T) TNT energy equivalent:

10^{12} calories
4.2×10^{19} ergs
1.2×10^6 kilowatt hours
4.0×10^9 British thermal units (Btu)
12.6 Gigajoules(GJ)

Although there is a substantial body of knowledge extant as regards NX device yield and the partition of the energies of that yield, most symmetric NX explosions have common qualitative and quantitative features. Illustratively, these are set out by R.E. Jones("-Nuclear Weapon Burst Parameters Governing Urban Fire Vulnerability", U.S. Naval Radiological Defense Laboratory, San Francisco, California, CFSTI AD 659,981, 24 pp., 12 ref., 24 May 1967), including the following aspects relevant to the present invention:

The initial phase of a nuclear explosion proceeds in a manner independent of the surrounding environment. Within a fraction of a microsecond after detonation, the fission products, device casing and ancillary, close-in debris, and like material, are raised to a temperature of several tens of millions of degrees. Before the explosion plasma has time to expand appreciably (within a microsecond), about 70 percent of the total energy present appears as "thermal radiation"(as it is called in that art) in the form of soft X-rays of several kiloelectron-volt energies, depending upon the temperature produced by the NX device. The remainder is primarily contained in the kinetic energy of the vapor-plasma entity, which expands until collision with the environmental medium at a velocity of about 0.5×10^6 feet per second.

In an air shot at about sea level or at low altitudes the primary thermal X-rays are absorbed within a few feet of the device, producing exceedingly high temperatures within the initial fireball. The energy is immediately reradiated and again absorbed in the surrounding air; hence, the fireball grows at high velocity as the radiant energy diffuses outward. Since the mean free path of the thermal radiation in air at these temperatures is large compared to the fireball dimensions, energy is rapidly distributed within the fireball, and the temperature throughout remains quite uniform as the fireball grows and cools. The mass of hot gases(or plasma) in the region behind the radiation front is referred to as the isothermal sphere.

The spectral distribution of radiation from the fireball can be approximated by the spectrum of a black body corresponding to the surface temperature of the fireball. In the more conventional NX explosions, which are not necessarily dealt with herein, only relatively low energy(visible and near-visible) radiation, a small fraction of the total, escapes from the immediate vicinity of the isothermal sphere during the early stages, and substantially all of the short wavelength radiation is reabsorbed by the surrounding air.

In the nuclear explosion art it is generalized that fireball temperature at the second thermal maximum(92 in FIG. 6) decreases slightly as the yield of the NX device increases, not considering the aforementioned phenomena dependent upon a surrounding gaseous medium. An approximate function which describes this variation derives from knowledge of the thermal pulse shape and fireball size(note is made, again, that this is essentially an uncontained fireball; and that evidently little is known about highly, partly or vented subterranean fireballs in this respect, which is quite germane to the improvement here addressed to) and the Stefan-Botzman law for the power emitted by a black body;

$$p = \sigma A t^4$$

where:

P = the power
t = the temperature of the body
A = the emitting area
σ = the Stefan-Boltzman constant

and that:

$$t_p = (P/\sigma A)^{1/4}$$

represents the power temperature of the fireball. Note is to be made of A as not being equal to that of a sphere, $4 \pi r^2$, in the present improvement because of aperture or throat or FRO surface of the optoexplosive light generator.

Subsequently, there is a sequence of radiation-pressure mechanisms, explained usually on a hydrodynamic basis, the temperature drops to a typical value of just under 10^4 °C, with most of the radiation lying in the visible, and corresponding to the time when the fireball reaches maximum size. Roughly, approximately 30 to 40 percent of the NX device energy is converted into thermal radiant energy, the preponderance being in the visible and near-infrared portions of the spectrum, with the balance as kinetic blast energy, i.e., at about atmospheric pressure. The spectral distribution of the thermal energy does not exactly correspond to that of a black body, and is depleted in the ultraviolet and the infrared.

However, viewed as a Planckian radiator a good approximation is obtained for the conventional NX explosion at hand: For typical fireball temperatures the Planck spectrum predicts about 10 percent of the energy in the ultraviolet, 40 percent in the visible, and 50 percent in the near infrared. Likewise, for the usual, non-optoexplosive NX device, i.e., the NX device not optimized for the generation of optical radiation, as should be the case in the present improvement in certain of its modifications, about 1 percent of the total thermal energy is released in the prompt pulse(90 in FIG. 6), with about 99 percent in the second pulse(92 in FIG. 6) which is radiated over a much longer period of time and at a lower temperature.

At NX burst altitudes of approximately 50 miles— or the equivalent in a depressurized optoexplosive system—the atmosphere can no longer be assumed isotropic, since the mean free path of the primary thermal X-rays(and thus the radius of the initial fireball) balloons to some tens of miles. Because of the density gradient, in a high altitude explosion, the otherwise spherical fireball becomes spheroidal, prolate above and oblate below, and at even greater altitude equivalents the distortion will be extreme. The thermal

radiation at ground level will consist of two main components: (a) a brief flash of a few microseconds lifetime, the visible and near-visible tail of the high-temperature NX device plasma spectrum being followed by (b) a pulse of longer duration emitted by the excited region of the tenuous atmosphere. The extra-visual portions of the spectrum may be enhanced.

Viewed simplistically the fireball from a just-detonated NX device, as well as that from a CX device, is a "plasma balloon," having high-rise rate(several hundred feet per second in the case of an open NX burst, more slowly in the case of CX detonations) and unique buoyancy—maintaining a certain structural and configurational integrity until it breaks out, as by hydrodynamic separation.

Thus, when a T or Y or like bifurcated explosion leg (e.g., 96,102 in FIG. 7, and 110, 120 in FIG. 8, with the light-traversing legs 104 and 117, respectively) carries an optoexplosive source(say at 10*e*(FIG.7), 10*f*(FIG. 8), and the other members shown in these drawings are not present), the explosion of that source results in the plasma balloon I have described, which rises and thus removes itself from the line-of-sight communication with the FRO means.

By venting the top arm of the T or Y or the like, venting can be obtained; otherwise, rebound into the lower arm, with an essentially lateral to-and-fro fluid flow between the side-arms(with of course some escapement, depending upon the configuration of the system), to decompose and dissipate the plasma balloon.

Similarly, taking FIG. 7 as an example of a T butt configuration, should the NX device 10*f*(or a CX device, as may be desired), be emplaced in the lower arm 102 and detonated, the plasma balloon will first form and then be constrained by the walls of the system, forming a plasma piston which will shoot upwards into upper arm 196(again, in this illustration members 94, 98 and the like are not present). If arm 96 rises to and opens at the ground surface 20*e*, the thusly-formed plasma piston follows the course of least resistence and vents at that ground surface. However, the plasma traverses the T made with leg 104 and light 106 therefrom passes down 104; the duration of this pulse depends of course upon the length and velocity of the plasma piston, and in any event generally making for the production of a lengthy light pulse 106. The easement of the plasma in its movement from shot point within 102 and up into and out of 96(should the venting modification be involved and, as just pointed out supra, this may not always be desirable) can be obtained by making 102 and 96 of relatively large diameter as compared to leg 104, offering by least-resistance pathway a lessened spillover of plasma into leg 104.

Knowing the expansion velocity of an NX or CX fireball readily enables those in the art to calculate the length and therefore the duration of light pulse production when the throat diameter of leg 104 is also known(as by a systems-science-reduction to a least-parameter model), although in such calculations the fluid mechanical properties of the plasma generally enter into the figuring at a more refined level.

It is noted in these versions that the burst or detonation light from an optoexplosion is not utilized, for that prompt pulse of optical radiation largely is confined within the arm 102 of the T—or its equivalent. Rather, the highly reacting or "combusting"(sometimes called "afterburning") explosive and explosive device and optional (e.g., dopant) materials account for the light production. The situation is well adapted to the use of dopants as liners or means say upon the walls of arms 102 and/or 96(in the latter instance as when the plasma is made to rebound back-and-forth between 102 and 96 in a partially or fully closed T configuration, until dissipated). Likewise, such an arrangement is suited to the employment of optoexplosives characterized as of the long-lasting low-order detonation or near-pyrotechnic kind, so as to yield a maximum of plasma. Highly brisant optoexplosives are utilized when comparatively short pulse outputs are desired, although usually with concomitant insult to the structure.

Illustratively, if an optoexplosive detonated say off-alignment with 106 as in FIG. 7, e.g., emplaced in sump 102 for that detonation, and within 10 milliseconds produces a fireball of 15 yards diameter, then the unconfined(as when 102 is larger than 15 yards in diameter) plasma balloon will occupy a volume of approximately 1750 cubic yards. Fifteen milliseconds later, when the plasma balloon is 50 yards in diameter, i.e., at 25 milliseconds from detonation, the spheric plasma body mensurates out to 6500 cubic yards volume. Assuming a cylindrical member like 102 in FIG. 7, and knowing its diameter, the rough length of the plasma piston formed once the plasma balloon is constrained and formed into the piston by arm 102 conveniently follows from the usual relation for the volume of a cylinder, $\pi r^2 l$(r = radius, l = length); or when of square cross-sectional face from $S^2 l$ (S = face side, l = length); or when of hexagonal section, $0.866 f^2 l$(f = distance between opposite faces of the hexagon, l = length of the hexagon); or when of octagonal form, $0.829 f^2 l$ (f and l, as before); and the like, including frustrum-joined configurations(as 102 and 96 in FIG. 7) at the intersection with leg 104 of FIG. 7(which, for example, may be round, elliptical or the like), like variously truncated cones and polygons, e.g., a pyramid.

The explosive coursing of a plasma mass from one side arm into a second side arm in communication therewith, and passing by an apertured stem(as illustrated here by shot within 102, traveling past 104, and through to 96 in FIG. 7), with stem 104 offering pressure release and shock dynamics like diffracted shock, secondary or reinforced reflections, and Mach-stem effects involves attendent fluidics, hydrodynamics, plasmadynamics and gasdynamics, among other features, which will not be detailed here, as these involve computerization for the solution of situations concerning the spill into the leg like that of 104(FIG. 7) of plasma(which may be taken as fluidic medium) and of kinetic energies like blast.

The otherwise wasted energies of the spilled plasma and blast, into the leg 104 optically coupled with the FRO means, can be reconstituted as useable optical radiation. For example, as by the employment of 104 dopant liner to take up and reradiate plasma energy; as by the use of fast-time fluorescent transducers for the same purpose; and as by loading part or all of leg 104 with luminously-shockable gaseous medium like a noble gas, with or without containing partitions singly or multiply sectioning out portions of 104.

Abruptly shock-densified nuclear reactant generates explosive energy by two processes: (a) fission, e.g., of uranium or plutonium isotopes, and (b) fusion, e.g., of deuterium and tritium, the latter forming out of the fragmentation of lithium-6. NX energy sources can be controlled by proper design of the device: The desired amount of energy can be metered out, although it is not always evident from available information just how this energy is partitioned; the release location can be designated and controlled; and the time of release of NX energy can be determined.

NX devices can be optimized in design for some single property or characteristic, although as I point out in the present disclosure, designs maximized for say the ultraviolet visible-infrared window of the atmosphere(of principal interest herein) seem to have received attention not at all or at least secondary to blast and other forms of energy. When small diameter or cost are paramount, these features can be designed into an NX device. Often there are trade-offs between the attributes of particular NX device designs.

Thus, herein the primary function of the NX energy source is an optoexplosive one, wherein optimizing for light output with or without attendent reaction rate change, and with or without dopants(as contrasted to "salting" agents which relate to another facet of the NX art), there is included: (1) varying the criticality and/or (2) varying the symmetry of the nuclear reactant, as for example singly or combined the following:

a. Reducing the criticality by lessening the enrichment of the nuclear reactant, as by alloying with the same element(but of different isotopic species), or by use of an additive element in alloy, solid-solution, chemical combination or like form, in which case the element(s) is essentially nuclear non-reactive and say of appropriate(e.g., low) neutron-capture cross-section;
b. Lowering the density of the nuclear reactant, as by explosive liquifaction(e.g., ensembling the nuclear reactant as liner, cone, filler or like element in one or more hollow-charges of the NX device), or by gasification-compaction techniques(discussed subsequently);
c. Reducing the reflected neutron flux, as by decreasing the surface area and/or changing the profile of the neutron reflector;
d. Changing the shape of the nuclear reactant by raising the surface-to-volume ratio, as by powder metallurgy and foamed-metal techniques;
e. Demoderating by reducing or modifying the moderation envelope;
f. Tamping, as by use of inclusives(e.g., particulates, cellulants(gas-loaded spheres and foamed-metal members), foil, rods, and the like-which may or may not act as dopants) characterized by appropriate(e.g., high) neutron-capture cross-section.

Furthermore, the performance of an NX device can be altered by suitably changing the nature, strength and configuration of the CX explosive media which actuate it.

Since the rise-time of the prompt pulse of an NX explosion may be of the order of 10^{-8} second (or 100 nanoseconds) (approximately the time constant for optical transitions in many substances, which value should be contrasted with the typical 10^{-13} second taken as reflection time), the foregoing can also be employed to: (I) change the rise-time by varying the nuclear reaction rate, and/or (II) expand the time base of pulse **90** and foreshorten or coalesce pulse **92** into **90**, making for more of a monopulse in FIG. 6, so as to provide a more useful optoexplosion, and, hence, to better match the optical absorption-reflection parameters of the FRO.

In the conventional NX device art and in the various nuclear explosions I have observed, the resulting explosion is usually regarded as substantially a symmetric one, i.e., spheroidal or approximating same until the point of environmental factor take-over. In certain versions of this invention(e.g., where venting, fireball plasma, and pressure problems are severe) I prefer to utilize an asymmetric or aspheric NX device explosion.

Asymmetric NX energy sources, for purposes of this disclosure, can be said to fall into two categories: (a) gun-type and (b) implosion, as follows:

a. NX source **10***d* in FIG. 5, for example, may comprise the usual constraining envelope carrying the necessary fissionable pieces, which are explosively brought together for the fission reaction by CX charges on either side of the group of pieces; however, in order to make the resulting explosion asymmetric or the analog of CX cylindrical explosions, with the preponderance of released energy emitted from one end of the tube over that of the opposite end, one of the two CX charges is stronger than the other. Thus, at the butt of **10***d* there is placed a more powerful shaped charge, whereas at the front(in the direction of **76** and **88**) there is placed a less powerful shaped charge, with the fissionable matter ancillary elements between the two. Other versions of this basic approach by asymmetric NX explosions, adapted to say multilegged optoexplosive system like that of FIG. 4 within design capacity of those skilled in the NX design art;
b. Likewise, in the implosion-type NX energy source one or more of the CX implosion "lenses"(as they are often called in the art) is of lesser yield than its opposing counterpart(s). The result, like that of (a), is that the explosive fission reaction(or fusion reaction, as the case may be) first breaks through at that portion corresponding to the less power of the implosion lens(es), giving asymmetry or a directed-energy explosion. There are many possible variations to this approach, utilizing multiple "break-out" implosion facets, which need not be detailed here.

One advantage of the directed-energy explosion, particularly NX, is that high Mach blast energies, debris and the like can be made to sink into the shock-sink leg(s) of the system; that more efficient venting can be had(see venting methods and means set forth herein); that insult to the firing chamber of the explosion leg is reduced; and that the problem of plasma piston handling in the case of high yield energy sources is expedited by sinking and/or venting.

The usual and more conventionally designed NX devices utilize nuclear reactant in solid form. Many NX devices are optimized for blast rather than optical energy output, and hence do not appear as well adapted to use in tellurian optoexplosive systems as they might be.

Since the requirements of a tellurian optoexplosive system may include NX energy generators of low yield(e.g., T to daT or, at least, in the sub-KT range), maximized for light generation and having reduced detonation rates(for longer light pulse production, albeit generally at lessened temperatures and efficiencies), I submit a gas-loaded NX energy source as an optoexplosive, which may or may not be doped to increase the color or brightness temperature.

Thus there is contained at suitable pressure a subcritical mass of say U^{235} in gaseous form, e.g., uranium-235 hexafluoride, $U^{235}F_6$(with the combining element(s) of low neutron cross-section or capture) within a CX implosion system. Upon firing the latter explosive pressurization of the fissionable gas compound takes place with compaction into a critical mass which undergoes low-grade nuclear explosion. Gasified plutonium compounds should also be useful. The nuclear reactant gas may initially be at elevated pressure, atmospheric pressure, or reduced pressure. The latter conditions are favored by the spatial latitude and large working volume available in the firing chamber of the explosion leg of the optoexplosive system. Immediately before use the gas-type NX energy source can be loaded by in-pumping gasified nuclear reactant from multiple (subcritical) bottles at the surface, the nuclear reactant container being of any suitable material used in the NX devices art. Modifications of the gun-type explosive source should be feasible for larger yield NX explosions, e.g., in the range of daT to several hectotons(hT), the gun envelope say being provided with a rupturable "window"(e.g., thinned and structurally weaker section) so as to give a directed-energy NX explosion and/or an NX explosion of controlled yield. Otherwise, asymmetric NX energy sources should result from proper use of implosives, as described in the foregoing.

Certain NX devices are designed for maximum neutron generation, and this is accompanied by an intense flash of light. The neutron energy of such devices can be transduced into optical spectrum frequencies by an appropriate neutron-excitable phosphor, with emission in the visible and extra-visible portions of the spectrum. The phosphor can, for example be turned to account as a coating on the walls of the explosion leg, preferably near the crotch where the FRO is emplaced, and/or by using a phosphor-surfaced FRO member. It is desirable that such a version be operated at reduced pressure, although it is feasible at atmospheric pressures or in tenuous gas atmospheres other than air, consistent with neutron absorptivities of gases. In the BARBEL ADD-ON event of 1961, an NX of special design produced an ultrahigh neutron flux which was collimated to a small beam for experimental purposes.

OPTOEXPLOSION MODIFIERS

By the expression "optoexplosion modifiers" I mean those adjunctive processes and agents, usually involving solids but not excluding gases and liquids, which chemically and/or physically interact with and modify the performance of an optoexplosive device or ensemble and/or the dynamics and kinetics of the reactions thereof which produce blast and light.

Optoexplosion modifiers and adjunctives take the two forms of: (I) incorporation with and into the optoexplosive energy source per se(e.g., dopants in intimate admixture with explosive substance), and/or (II) agents and adjunctives external to that source, but in close and reciprocal relationship with the dynamic explosion(e.g., decouplants).

Optoexplosion modifiers fall into a miscellany of overlapping classes, the functionality and exact role of which are sometimes overlooked or are upon very empirical bases in the more traditional explosives art. For working purposes herein these modifiers include the following:

a. Dopants: agents and/or processes which interact during the reactive, dynamical phase of the explosion, i.e., at some time during the first-to-last of the reaction, serving to enhance color and/or brightness, and/or functioning to add to and introduce into light output spectral qualities, e.g., particular lines and bands (both emission and absorption, the latter being especially emphasized here for those optoexplosion beams desired as characterized by spectral gaps), of the kind to be worked into an irradiable target; and, agents and/or processes which interact with the kinetic energy output, particularly shock, to produce usable light.

I demarcate the two aforementioned working varieties of dopants as follows:

A. Detonation dopants: those which physicochemically interact with and enter into the explosion reaction per se, including the combusting which may be involved in say the after-median or trailing edge of the detonation sequence, to provide adiabatically or otherwise excited atomic and molecular species or both(e.g., C, Si, B, Al, Mg, Zr, Hf, Ta, Nb, Th, U, and rare earths, and their various species like monoxides(as of alkaline earth metals), it being emphasized that the line between the usually small amounts of dopants typical to an enhancement process(involving detonation and/or combusting) and the generally larger amounts of the same or similar materials that more properly have to be regarded as daltonide(as contrasted to bertholide) ingredients of many of the usual explosives;

B. Shock dopants: those which interact with shock, blast and the general category which includes "-kinetic energy," which generally do not enter into the chemical reaction or affect the rate thereof, and which transduce essentially kinetic energy into optical radiation; e.g., the various gases like the noble gases, the more reactive and single element and compound gases and vapors(including those derived from sublimones) like N_2, O_2, N_2O, CO_2, CO, the halogens, and certain halogenated and group- or radical- coupled carbon compounds(e.g., fluorocarbons, metalorganics, nitrocarbons);

And, as is evident, kind (A)—detonation dopant— is an integral part of the explosive device or at least in interreacting relationship with or closely intimate to the reacting explosive mass; whereas, kind (B)—shock dopant—may be in an external relationship which includes reception of and interaction with the light excitant(shock) but does not necessarily exclude the highly dynamic phase (A) which due to pressure and similar

characteristics of its own may engage in a feedback relationship with the shock dopant situation;

b. Decouplants: substances external to a CX or NX device which, via entropification processes, reduce and degrade kinetic energies,; normally these are thought of in terms of NX energy sources, but here I specifically point out decouplant masses cooperantly arranged with CX sources of high yield, or of CX devices seated within and detonated in a tellurian optoexplosive system characterized by comparatively short and large aperture legs, and formed out of a medium of high seismic permeability;

c. Ablatives: agents of a rather arbitrary classification, e.g., overlapping for example (b), supra, wherein change-of-state like pyrolysis, vaporization, sublimation, fusion, and the like are involved. The situation is complexed by the fact that ablatives(e.g., forming melts, vapors, sublimones, spalled particulates), as from a tunnel or shaft wall of siliceous make-up, can and do contribute as a detonation dopant in that light output is increased. Conversely, ablatives can behave as decouplants by entropying and decomposing unwanted energies like those in kinetic forms and those at the extremes of the electromagnetic spectrum, particularly X-rays;

d. Optical transducers: usually fast-time fluorescent agents, e.g., pure emitters, phosphors, doped glasses, of less than approximately 10^{-8} second lifetime, and not excluding gases and vapors and liquids, albeit usually solids, which absorb optoexplosion exciting light and emit in a Stokesian mode; anti-Stokesian luminescents of suitable relaxation time are not excluded, although these comprise a small minority of the family;

e. Coolants: agents which interact with an infant, mature, or senescent explosion in such a way as to limit the rate of reaction or the temperature of the reaction(which kind of definition may be said to hold in converse for some dopants, supra); coolants are employed mainly in low-order detonation and pyrotechnic-type optoexplosives to regulate light emission by a given atomic or molecular species by keeping the reaction rate and/or temperature favorable for the existence of that species;

f. Velocity modifiers: agents or physical characteristics which increase or decrease detonation velocity within an optoexplosive mass, usually by changing the density. Entrained air and variations in crystalline state, e.g., ranging from the more dense cryptocrystalline to the less dense coarse or macrocrystalline, loosely a situation which is an analog of confinement, wherein the transition from deflagration through to detonation involves the former in a mode of explosion as distinguished from the latter by constituting the very rapid autocombustion of particles as a surface phenomenon; in deflagration the reaction products flow away from the unreacted material, while in detonation these are at exceedingly high pressure and flow toward the unreacted material (cf. W. Rinkenbach in G. L. Clark (ed.), "The Encyclopedia of Chemistry", New York, Reinhold Pub. Co., 1957, pp. 284–285; M.A. Cook et al., Proc. Roy. Soc., 246A, 281–283 (1958); M.A. Cook et al., J. Appl. Phys., 30, 1579–1584(1959)); the well known variation of detonation rate with density of explosives like TNT may be taken as an example. The density of an optoexplosive, and hence the detonation rate, can be varied by numerous methods and means: e.g., rate of cooling from molten state, gasification by inert or noble gas during the casting step, compositing by adding low-density filler or diluent, and loading with microencapsulated solid, liquid or gas.

Throughout the present disclosure I have set out illustrative and typical optoexplosive modifiers; these data may be complimented and reinforced by the following pertinent information and examples.

As just indicated, my concept embracing the dopant is a very broad one. It includes a large and variegated category of substances(and, in some cases, physical effects and agencies) not always neatly defined or classed in terms of chemical and physical properties. The more easily functional approach, however, provides certain common qualities which run through the solids, liquids and gases I have demarcated as detonation dopants and shock dopants. Generally, the common feature from the standpoint of functionality is simply the alteration of the balance of an explosion process in favor of light output of practicable and usable nature—to make for what I call an optoexplosion—and to contribute to the production of that optoexplosion optically transduced energies from otherwise unwanted and wasted optical, chemical and kinetic energies.

Dopants may or may not be Planckian, and they may raise the system to one or more optical parameters—real or apparent but, in any event, useful—to that level beyond what would be expected by application of black body law, spectrum-additive-dopants included. Likewise, dopants in an explosive configuration may result in an optical output above that usually set by stoichiometric and thermodynamic and like considerations.

Throughout this disclosure I have endeavored to emphasize dopant and like agencies in the particular reactions set out. For example, that of the oxidation of cyanogen, where in the presence of carbon a several-fold enhancement results; or in the case of high detonation rate chemical explosives like TNT, PETN, RDX, where the addition of metal powder like aluminum may nearly double the energy; the same thing being true of low detonation rate explosives like black powder (where an essentially "carbon flash" is changed to an "aluminum flash"), and so forth.

Carbon, an example of a dopant in a high explosive which is otherwise of low luminosity, leads the way to a class of dopants which may be described as "high temperature." These are the substances noted with respect to refractory FRO means, set out by J.F. Lynch et al.(cited herein), which are solids until the ca. 10^4 °C region is attained(e.g., carbides of tantalum, niobium, zirconium and hafnium). Certain of the nitrides and silicides fall into this category.

Certain silicon alloys possess a dopant quality, causing an increase in brightness when added in percentages up to approximately 5–8 percent. For example, I have tested calcium-silicon alloy(e.g., Ca(28–35):Si(60–65), an example of alkaline earth metal:silicon

alloys, and have found that there is a pronounced enhancement in the light-giving qualities of pyrotechnic compositions of the fuel-oxidizer type having a combusting or deflagrating temperature in the range of less than 10^3 °C.

Dopant-enhanced light output appears generally within the area of chemical explosives and explosions. At first sight detonation and like dopants would not seem to be applicable to nuclear explosions, aside from shock dopants like noble gases which interact in the usual way with the shock front. However, despite the often different energy levels between the CX and NX explosions and the means producing them, there are features which allow for detonation doping and, therefore, the use of dopant(s), in the NX energy process.

Thus, in both prompt flash and particularly the afterburning fireball luminosity dopants either are present by virtue of NX device design or of nuclear reactant; Thus, the casing and like immediate and adjacent material contribute to both, as is the case when the nuclear reactant is say not highly enriched and the diluent contributes to the nuclear burning process. When the temperature of this process drops into the 10^5 °C, or at least below 10^6 °C, the high temperature dopants, supra, are advantageously employed. Likewise, dopants such as certain metals and metalloids, W, Nb, Ta, Si, B, can be utilized.

These are usually in particulate form in a mass in which the NX device is embedded, of symmetry characterized by a larger mass of the dopant at the rear(away from the leg leading to the FRO) of the device. Special ensembles and geometries can be employed for directed-energy NX devices so that maximum nuclear energy is taken up by the dopant body.

Taking the nuclear plasma as an analog of flashlamp plasma of high power, gas-discharge type, the nuclear plasma in a siliceous or artifically-prepared(as by shaft or tunnel coating) tubulation can be expected to produce what is called in the flashlamp art "impurity radiation" from the "evaporated" wall surface material. When the system design is such that nuclear plasma(and the same holds for CX-derived plasma, in both cases afterburning or combusting material of high energy and a high degree of ionization of elementary particles like atoms) passes into the explosion leg, that leg may be lined with dopant(e.g., high temperature variety) or have projections out from its walls made of the dopant.

The concept and principle of decoupling and the use of decouplants derives from the NX device art. Thus, the signal produced by a given underground burst depends upon the nature of the medium within which it occurs. This is due to the difference in magnitude of kinetic(or mechanical) energy transfer(or coupling) between the explosion and the surrounding tellurian medium. For example, tests have been made on the seismic effects of CX energy sources in saltine medium with TNT charges up to 1 T in size. Although the extrapolations into NX device shots of the KT range indicated that a saltine medium would have a decoupling factor of 2.5 for a tamped shot in tuff, the GNOME NX shot(December 1961) of about 3–4 KT, also in salt, shows that in these yield ranges the salt has a coupling(as contrasted to a decoupling) factor of about 2.5 under similar conditions. However, by use of a large hole for emplacement and shot of the NX device, the apparent yield of that device can be pared down to between several tenths and several per cent of the original value in terms of the seismic signal generated. In the sense of "decouplant", as generally used here as behaving cooperantly with an NX or CX explosion to take up unwanted kinetic energies in particular, graphite is an example of a material which by heat and like absorption—entropification via change-of-state—decouples by a theoretical factor of 3×10^3 or more, although evidently not all skilled in the NX art agree with this(cf. "Technical Aspects of Detection and Inspection Controls of a Nuclear Weapons Test Ban," Summary Analysis of Hearings, pp. 26–27, 74, Joint Committee on Atomic Energy(U.S.), Washington, D.C., April 19–22, 1960).

Typically, for present purposes the NX device-decouplant arrangement is specifically structured so that, for example, within the firing or explosion chamber of the explosion leg of the system, said chamber being enlargened in appropriate manner and geometry and size, the optoexplosive device—NX or CX or both—is surrounded by decouplant, except that the portion facing the explosion leg and thence to the FRO element (e.g., device 10*f* in cavity to 122, facing into 117 and providing optoexplosion light 118 in FIG.8(the other features in this drawing are omitted for present purposes) is not surrounded by decouplant so that optoexplosion light 118 can traverse leg 117.

The structural arrangement between NX or CX or both and the decouplant, taken together with the chamber size, is made in accordance with shock and explosion phenomena, and can be as fully decoupled an arrangement as possible consistent with the generation and liberation of light into leg 117, or a partially decoupled arrangement. In the latter case there may be an intervening space of an atmosphere, and the member 122 or its equivalent comprising the decouplant. In such a version slabs or briquettes of graphite or other heat-absorptive material, which may be an endothermic chemical composition or a simple change-of-state material like a conventional ablative, say composite wherein randomly oriented fibrous, particulate or other dispersed solid within matrix solid like thermosetted polymer is utilized.

Decouplants of the ablative species(not to be confused with "ablatives" as modifiers also set out herein) can be chosen and designed out of experience with entry materials, heat shield substances, and the like in the missiles field. This is the subject of a large literature and the artizan is referred to such examples as: H.G. Landau, "Heat Conduction in a Melting Solid", Quart. J. Appl. Math., 8(1), 81–94(1950); R.G. Fleddermann, "Analysis of Transient Ablation and Heat Conduction Phenomena at a Vaporizing Surface," Chem. Eng. Symp. Ser., 57(32),24(1960); H.Bethe and Mac C. Adams, "A Theory for the Ablation of Glassy Materials," J. Aerospace Sci., 26(6), 321–328(1959); R.S. Barriault and J. Yos, "Analysis of the Ablation of Plastic Heat Shields that Form a Charred Surface Layer," J. Amer. Rocket Soc., 9, 823–829(1960); H.S. Carslaw and J. Jaeger, "Conduction of Heat in Solids," London, Oxford Univ. Press, 1959; J. Kanzlarich, "Ablation of Reinforced Plastics for Heat Protection," J. Appl. Mech., 3, 177–182(1965).

I particularly cite these and like references herein to exemplify those facets which deal with the state of the art not only as it may concern decouplants and candidates for that role, but also in connection with facets relevant to other kinds of optoexplosion modifiers, e.g., optical transducers(as physical configurations, for example), coolants, and velocity modifiers. Furthermore, operancy of the various forms of the FRO means relates to this area, e.g., timed-life FRO and reflectively-changeable(during input pulse history) FRO.

When I speak of ablatives as a category of optoexplosion modifiers I distinguish these from dopants and decouplants which in certain instances involve ablative behavior, admitting that again there is overlapping between the classes; but at the same time pointing up the fact that certain materials within or interacting with explosion plasma contribute materially to light generation. For example, it is recognized as a fact that high power gaseous discharges(plasmas) are acompanied by "impurity radiation" evolved from "evaporated" wall portions of the envelope—these are called "ablative light sources." In these sources the major portion of the radiation is emitted by the wall particles rather than by the gas initially loaded in the electric discharge tube. The ablated wall material may be fused silica or a thermoplastic like lucite(methyl methacrylate), and in connection with the present improvement I would especially emphasize the following ablatives: non-silicates, e.g., boron and phosphorus based glasses; heavy metal(like lead) and rare earth glasses; heavily doped("impurity") glasses; and the like.

When the shot vault and/or explosion leg of the system, e.g., 14 back to and including means 10 in FIG. 1, is of highly siliceous material like granite, granodiorite, rhyolite, or the like, it can be considered the analog of the envelope of an ablative light source of the electric discharge variety. In the latter the conversion of electrical energy occurs with an efficiency of between 10 and 30 percent, in the microsecond domain, with a good proportion of the emission in the ultraviolet. Thus, R. Goldstein and F.N. Mastrup(IEE J. Quant. Electronics, Q-3,249(1967); J. H. Gonz and P. Newell, J. Opt. Soc. Amer., 56,87(1966); see especially, for summary and review, A. Papayoanou et al., "High-Power Incoherent Light Sources", CFSTI AD 664,148,11 pp. (cf. pp. 8-9), Fort Monmouth, New Jersey, November 1967), establish an increase by a factor of 5 due to ablatives, ranging down to 3500 A in the case of silica.

Papayoanou and Buser(cited above) reinforce the objects and features of the present and parent inventions by stating that a plateau has been reached in the use of standard (electrically-powered) flashlamps as pulsed incoherent light sources, and that deficiences are pronounced in very high power ultraviolet light sources.

A fluorescent solid having a very fast transition time, e.g., phosphor or doped fluorescent glass (preferably comprising high temperature host material), behaves as a transducer in that particulate radiation and short wavelength optical radiation is absorbed, with emission in the ultraviolet, visible, and/or infrared portions of the spectrum. Many such substances are known and need not be detailed herein. Substances of high quantum efficiency are preferred. Such a fluorescent transducer enables an upgrading in efficiency of an optoexplosive light source in that otherwise wasted light or particulate energies are converted into useful light.

The fluorescent transducer may be coated on the wall of the explosion leg and/or layered upon say a frangible, reflective metal substrate. In the former instance an optical arrangement of wall-projecting reflectors gathers the initial exciting light (the reflection surface faces the explosive light source), and then directs it to projecting members which carry the fluorescent transducer (which faces the FRO), say as a spaced series of half-pyramids (the flat or curved faces being the reflection and transduction faces.

When fluorescent transducer excitation is to be made by particulate radiation, the system is preferably outgassed so as to reduce absorption and increase mean free paths, depending upon the particle(s) involved. For neutron beams tenuous air or low cross-section gases can be loaded into the system. For increased luminescence efficiency the fluorescent substance can be supercooled, and this is particularly desirable in the case of a large fluorescent mass carried in the form of an FRO element at the crotch of the optoexplosive system.

An example of a calculation of the maximum brilliancy of a phosphor excited by an unlimited energy input is that of H.W. Leverenz(R.C.A. Rev., 5,162(1940)):

$$E_{max} = ZPE/t$$

where:

E = the luminescence energy in ergs;
Z = the optimum concentration of activating centers per millimeter, being 10^{21};
P = the penetration of the exciting electrons into the phosphor layer, in centimeters;
t = the transition time for luminescent output in seconds.

In a typical calculation this comes out to 9×10^{12} ergs per square centimeter, or about 9×10^5 watts per square centimeter.

Coolants form an assortment of often seemingly little-related compounds. Flash reducers and flash hiders of the munitions art, and certain ingredients common to pyrotechnics are included as coolants. Federoff et al.("Dictionary of Explosives, Ammunition and Weapons(German Section)", PATR No. 2510, CFSTI AD 160,636, 343 pp., Dover, New Jersey, 1958, p. Ger. 51) lists the following substances which have been used, most of which date back many years in the pyrotechnic art: potassium salts like the sulfate, nitrate or oxalate; alkali salts generally, with improved performance going up the series in the periodic system, e.g., Cs is better than Rb and Rb is better than K; oxalic acid; potassium chloride; sodium bicarbonate; nitroguanidine(an explosive in its own right). A.A. Swanson and D.D. Sager are cited(by Federoff et al., supra) as examining the following compounds as flash reducers:

Aminoguanidine bicarbonate; ammonium acetate, phosphate, sulfate; apatite; asbestos; barium sulfate; boron nitride; cerium oxide; cryolite; dicyandiamide; dimethyl oxamide; dimethyl urea; disodium phosphate; mercurous nitrate; methylene urea; potassium bicarbonate, chloride, iodide, metaphosphate, perchlorate,

phosphate, silicofluoride, urea oxalate; sodium ammonium sulfate; sulfur; zinc sulfate; and zirconium oxide.

The explosive flash of an exploding projectile can be reduced to the point of flashlessness by surrounding the explosive body with a 5 to 6 millimeter layer(sheath)of chlorine containing material such as ammonium chloride, tetrachloronaphthalene or hexachloronaphthalene.

Additionally, in my investigations of deflagratives and like munitions I have successfully used such compounds as alkali acid sulfates(e.g., $KHSO_4$, alkali carbonates and bicarbonates and oxalates(cf. U.S. Pat. No. 2,995,526, p.3; also, various items on fluorescent, radioactive, carcinogenic and like specialty smoke-forming pyrotechnic munitions in Official Gazette(U.S. Patent Office) and Chemical Abstracts for the period of early 1950 and on).

When compatible with other optoexplosive material coolants can be added in small amounts, e.g., of the order of several percent(depending upon the result desired). Or, such agents can be arranged cooperantly with such explosive material but isolated therefrom, as by barrier or layer partition using thin plastic film to form a laminate; coolants can also be prilled or coated after the manner of the pharmaceutical art; microencapsulated coolant agent may be employed to advantage.

BEAM MANIPULATION — LARGE AREA OPTICS

The shock- and debris- freed optoexplosion light may be variously manipulated or fashioned, and/or applied to target in one or more of the following ways:

a. In its pristine form, as delivered by the FRO means, as in the case of CAL;
b. In the form of collimated and/or sectionally-shaped raw light, as in the case of SAL;
c. In the form resulting from alteration by one or more passes involving reflection and/or refraction optics, with or without special treatment by such optical devices as beam-splitters, polarizing elements, and electrooptic switches, particularly what I call "flux-varied"(i.e., across the face) beams.

As it issues from the light leg of the system the beam may be collimated or otherwise passed through one or a series of stops, diaphragms, slits, or like aperturing means well known in optics, with scale-up commensurate with the beam size and energy.

As regards ancillary optics which shunt the light to the target mirror lenses are by far the more efficient and economical when large-body beams of light are manipulated. The mirrors are usually formed metal sheet of highly polished and reflective surface, although they may be first surface, metallized glass, plastic or metal. The glass and the metal have the advantage of rigidity in large sizes. The plastic is advantageous from the standpoint of low cost and light weight. The glass base, and in the case of thermoplastics, may be formed by the technique of slump-molding over a master mold. Should pressure of blast effects be involved to a slight degree by spillover from an improperly vented or over-explosived system, the mirror elements may be perforated in one or more places, though not to the extent of reducing to a great extent their light gathering surface. Extra-large area mirror lenses may be made and assembled in sections, as from a number of pie-shaped wedges tied together, which approach is often feasible and desirable when otherwise untransportable mirrors are involved, e.g., because of large size, need for structural and form integrity.

A low-cost, easily-handled and formed mirror optic is that of the inflatable balloon(or like structure) variety. This is simply a round bag adapted to air or other gas filling, having temperature-resistent fabric(e.g., Teflon, asbestos or organometallic polymer) metallized on its optical face, with or without reinforcing stays or like members. Lighter-than-air gas(e.g., He) filling, together with tie-down cable, enable positioning the "aerial optic" at any convenient or reasonable altitude, in the appropriate beam shunting attitude, above the exit portal of the usually ground-surface light leg. Thin metal or plastic stays, girders or like members serve to form the optic(e.g., as an ellipsoidal or paraboloid mirror) and to maintain the integrity of that shape involved. High winds, of course, and to some extent heavy rain, limit the performance of such an aerial optic. The reflecting portion of the aerial optic, alternatively, may be a sheet of polished metal foil or metallized plastic film. Numerous design, structural and functional variates of the inflatable optic will be evident to those skilled in the art, and for approaches to the bases of these reference should be made to the literature on inflatable structures and balloons.

Optically, the mirror lens(usually paraboloid or ellipsoidal in configuration) can be the first and only member to gather the optoexplosive light, to pass it to the irradiable target. Or, such a reflection optics system may comprise more than one mirror lens, as for example double-ellipsoidal and double paraboloid(two mirrors in each system), single compound reflective system, and double compound-reflective system, including flux distributors. For optics design information the artizan should consult P. Glaser and G. Walker, "Thermal Imaging Techniques," New York, Plenum Press, 1964; H. Lazlo, "Image Furnace Techniques Survey," Solar Energy, 7, 4(1963); and, "The Use of a Kaleidoscope to Obtain Uniform Flux Over a Large Area in a Solar of Arc-Imaging Furnace", by Chen, Mattack, and Glaser, Applied Optics, 2(March)1963.

Like the primary optic element in an optoexplosive system, the FRO, secondary optics such as mirror lenses may be adapted to selectively and preferentially change the flux value across the face of the reflected light beam. The same technique can be used for secondary reflectors as for the FRO, singly or in combination therewith; namely, modifying the surface of the mirror between one of highly specular and one or highly diffuse reflectances. When this is done in desired or predetermined pattern the resulting beam will, in its cross-section, exhibit the lower energy densities due to loss by diffuse reflection and the higher energy densities resulting from specular reflection. This and like methods are more suitable for light beams which are not brought to focus upon an irradiable target, and where that target truncates the beama short distance below the actual or calculated focal point.

Alternatively, "flux-shaping" may be had by a composite secondary mirror; that is, one made up of materials of given patterning, and of different reflectances.

Like large-area reflection optics, large-area refraction optics need not be the elegant and sophisticated ones of fine optics, although it is always desirable to engineer an optoexplosive system to within reasonably good working tolerances. Surface imperfections, microbubbles, striae and other defects are generally not of importance in large-area optics, being compensation-cancelled by the area.

Large-area refraction optics are less desirable for the reasons just mentioned. However, in those special cases where they are necessary, and in the smaller optoexplosive systems, refraction optics are sometimes advantageous, e.g., they may be more rugged and suited to a series of shots. Such optics can be fabricated by molding(one-piece or compositely), or by the slumping methods of the art when glass or optical thermoplastic is the medium. About 110 "plastic glasses" have been described by H.C. Raine("Plastic Glasses", Proc. London Conf. Optics Inst., 243 et seq. (1950); Amer. Inst. Physics Handbook, "Optical Plastics", p. 6-19, New York, McGraw-Hill, 1957).

The so-called optical glasses are tabulated for refractive indices and reciprocal dispersive powers; chemically they include vinyl polycyclics, polycyclic acrylics and their esters, and halogenated styrenes—among others—as well as certain metal derivatives thereof(e.g., Pb), with refractive indices (n_{20}) ranging between approximately 1.41 and 1.68.

To meet the need for large-area optics of the (a) refraction (lens) type, and/or (b) light-guide type(e.g., fiber and plate light pipes or conduits), wherein there is a refraction interface situation, I have designed and tested on a modest basis the two aforementioned kinds, emphasizing that this new class of optics is primarily designed to gather and refractively guide incident light—with beam shaping according to the geometry of the device—with resolution, chromatic aberration, and like qualities of fine optics secondary.

I call these "wound-optics." Thus, in simple form, take a strip or tape of transparent thermoplastic and tightly wind that strip into a roll upon itself, so as to form a flat roll like a roll of common tape. The start of the winding can begin upon a small-diameter mandrel or rod of the same plastic. From this product there is derived:

a. A plate-type light-guide when the faces of the tape roll are substantially plane and smooth. Should they not be smooth, the body of rolled tape can be chilled(e.g., to the glass point of the polymer), and in the resulting brittle form cold-lapped by fine and gentle abrasive action to produce a plane, polished surface. Because of the air layer of lower refractive index between the layers of plastic tape the product behaves as an incoherent light guide. As desired, instead of lapping and polishing, a coating of suitable lacquer can be put upon the faces;

b. An obvious alternative to the form taken by the wound optic of (a), supra, is that in which the polymer tape surface is first coated with viscous liquid like a polyalkyl silicone polymer(e.g., a silicone) of suitable refractive index for the material used;

c. When the thermoplastic roll of (a), supra, is placed in an oven and very gently brought to melding(i.e., interfusion of adjacent layers) temperature, preferably with a mild negative pressure(to degas so to prevent bubble formation from entrained air or volatile plasticizer), the product is now ideally a roundel slab of optically and physically homogeneous material;

d. If, instead of a rectilinear strip of thermoplastic there is employed a polymer strip of side-elevation contour corresponding to a halved bi- or plano-convex lens shape, and the winding is started at the truncated portion, there results a roll of bi- or plano- convex lens configuration, which may be heat-melded;

e. Conversely, instead of a rectilinear strip of thermoplastic, should the strip in side-elevation correspond to a halved bi- or plano- concave lens shape, and the upon-itself winding begun at the long-axis verical half-cut, there results a roll of bi- or plano- concave lens configuration, which may be oven-treated to give a substantially homogeneous body;

f. I would now expand upon the foregoing techniques of wound-optics, including same but not excluding other methods embracing heat-workable polymers, glasses or the like(including particulate and concentric-mold techniques) to derive what I call "plate-lenses"(i.e., substantially flat plates of circular or polygonal or other sectional geometries). Plate-lenses are characterized as refractively manipulating an incident beam of light into a convergent or divergent beam or the like. While, typically, such optic elements are parallel-plane plates, not excluded of course are plates of spheric facial aspect, consistent with the positive or negative magnitude of the lens desired. The materials approach to the fabrication of plate-lenses is exemplified by the series of acrylics:

Substance	Refractive index (rough value)
tert-Butyl methacrylate	1.464
Isopropyl methacrylate	1.473
n-Hexyl methacrylate	1.481
n-Butyl methacrylate	1.483
Methyl methacrylate	1.491
2-Methyl-cyclohexyl methacrylate	1.503
2-Chlorocyclohexyl methacrylate	1.518
Methacrylic anhydride	1.523
Butyl mercaptyl methacrylate	1.539
b-Bromoethyl methacrylate	1.542
p,p'-Xylylenyl dimethacrylate	1.556
Benzyl methacrylate	1.568
2,3-Dibromopropyl methacrylate	1.574
a,b-Diphenylethyl methacrylate	1.581
p-Bromophenyl methacrylate	1.596
Methacryl phenyl salicylate	1.600
Pentachlorophenyl methacrylate	1.610
b-Naphthyl methacrylate	1.629
Fluorenyl methacrylate	1.632
Lead methacrylate	1.645

When a series of several or more strips of the foregoing or equivalent materials is made say by lap-splicing individual members into a single length of tape, and this tape is tighly wound upon itself to form a roll, there results a plate-lens which is either positive or negative. When the roll is started with the material of higher refractive index and ends at its periphery with the material of lower refractive index, a positive lens results; and vice versa. The magnitude of the positive or minus quality depends the index intervals and the homoheneity of the resulting heat-treated body, other things being assumed equal. Of course the plate-lenses

are not designed primarily as image formers, rather they are optics which may be said to be "quasi-coherent" in they they function to gather light and refractively shape a transmitted beam into diverging or converging, as the case may be.

What I call "stacked-lenses"—characterized by large area and low cost—can readily be made by piling a series of transparent plastic(or glass or polycrystalline optical substance) plates or sheets, each sheet having a slightly lesser diameter than the sheet beneath(as in building a plano-convex lens); or by stacking a series of sheets of decreasing-diameter O-rings, with a final disk plate for the center or last element in the sequence(as in building a concavo-convex lens); or by stacking a series of O-rings of the same diameter but of decreasing hole size from bottom to top, the bottom plate being discoid or roundel without hole. Aplanar bi-lenses result when two of the stacks(of like kind) are placed face-to-face or back-to-back(plane areas meeting).

The piled or stacked plates are then made into a more or less optically homogeneous mass by one or more of several treatments. Thus, just prior to stacking and arrangement the contact faces of the plates are lightly and evenly coated with plastic cement of base the same as the plastic being employed for the lens fabrication; slight side-wise sliding before drying can be used to eliminate unwanted air bubbles. Or, the stack, with or without the cement, may be placed in an oven and gently heated under outgassing conditions(to pull off entrained air) until fusion occurs between the layers, with a resulting solid body.

In certain instances(e.g., extremely large area optics) it may be desirable to screw-bolt or dowel the stack, using bolts or dowels of the same plastic(suitable plastic cement is again usually employed).

The stacked-lenses can be used as-is or, preferably, given a final working, as by lapping to remove the steps between the plates or sheets, and to optically contour and finish the surface. Since the polymers used are usually thermoplastic, slumping over a master form can further be employed to shape the product.

Like aerial or inflatable optics, reinforcing ribs, stays, and like structural members can be incorporated into the design for strength and to prevent gravity sag; or, suitable mechanical mounting can be used for the same purpose.

And, after the fashion of the fresnel filters described below, a large family of very interesting optics results when stacked-lenses are made from sheets of material of different refractive index(cf. the discussion herein on plate-lenses).

The foregoing principles may also be utilized to fashion aplanar substrates for large mirror lenses, appropriately low-density and high-rigidity material being selected(e.g., plastic, foamed plastic, plastic-glass composites, balsa wood).

When the secondary optics, if any, in the system are of the refractive kind, or it is desired to rely upon a transmitted pass of light instead of a reflected one, the aforementioned "flux-shaping" or energy density patterning can be accomplished by a composite body or stack of neutral density filters, i.e., plates or sheets, each graded between wholly transparent and shades of grey and wholly black or absorbent; individual members of the laminate correspond in shape and transmissivity to the result wanted.

Alternatively, and preferably when maximum light is to be had, is such a stack of the same or preferably different refractive indices, the sheets or plates otherwise being transparent for the portion of the spectrum being worked. Such an optic, in effect, is a fresnel filter, performing out of the well-known law(for an air-isotropic solid interface(e.g., plastics and glasses or the both in combination): $R = (n-1)^2/(n+1)^2$. A simple example of such a fresnel filter is that of two roundels of plastic and/or glass held together, one of the roundels being smaller than the other. Depending upon the refractive index differences, and taking into consideration the increased number of multiple internal reflections occurring between the two(and to some extent the layer of air in between), the flux-shaped beam transmitted by such a device will comprise a ring of light of greater or lesser energy(usually lesser) enclosing a circular beam of different flux, depending upon the optical qualities of the materials employed.

Taken together with their large areas and variegated refractive characteristics the various refraction optics I set forth herein are pecularialy suited to operate as an Andrew's Separator(W.S. Andrews, Genl. Elec. Rev., 9, 817(1917)). This system enables the isolation of spectral regions by virtue of chromatic(i.e., wavelength or frequency) aberration, wherein radiations of longer wavelength are less refracted than those of shorter wavelength. Thus, to provide shorter wavelengths in the ultraviolet, visible and/or infrared, or, especially, to isolate regions from each other within the ultraviolet and infrared, a ring-stop(or, for rough work an open stop or diaphragm) is placed before the lens-emergent beam at that point where a particular spectral region is to be passed and the adjacent spectral regions are to be cut off. Various refraction optic + field stop arrangements can be employed, and the technique has been elaborated upon and extended by A. Terenin(Physik Zeit., 31, 33(1925)), and by G.S. Forbes et al., Rev. Sci. Inst., 5,253(1934)).

IRRADIABLE TARGET

Reiterating and amplifying my original disclosure on irradiable targets: The target may be of any appropriate shape and form, of solid, liquid and/or gas, at ambient, elevated or reduced temperatures and pressures, contained or uncontained, and with or without special envornment of solid, liquid and/or gas, as may be desired. Solid irradiable targets, unless transparent, like liquids, present the best attitude towards the FRO shunted beam when in layered form. Ancillary backing or retroreflection or like means can be used to conserve the light by passing it back into the target after the initial pass.

The target is usually stationary, mounted so as to receive the beam; however, the target may be of the moving kind, in which case the incidenting light and target movement are synchronized. The target may be positioned at ground level(as at 30 in FIG. 1), partly beneath the surface(as at 30*c* in FIG. 4), just beneath the ground(as at 30*a* in FIG. 2), deeply subtellurian(as at 30*b* in FIG. 3), or set above the surface in a close or distant relationship with that surface(as exemplified by 30*d* in FIG. 5).

Typically, exceedingly large optical energy fluxes can be deposited in a target for purposes of heat treatment, fusion, evaporation, crystal growth work, induc-

tion of thermochemical and thermophysical change, molecular disruption, excited radical production, electron-stripping of atoms, and the like. The investigation and production of very high melting refractories, alloys, eutectics, and the like is expedited by ultrahigh power optoexplosive light generators. In many instances the mass of substance to be irradiated can act as its own crucible, with say a core portion that is impacted and treated. In certain cases the so-called magnetic-suspension or magnetic-floating techniques can be utilized to isolate a target from its surroundings.

Becase an irradiable target is apt to explode when large optical pulses are injected into it, it may be desirable to irradiate within a container and atmosphere of transparent, inert gas at elevated pressure, such a container ensemble having say a thick window of fused silica. A less complicated container for use under such conditions is one of elongated neck, made of high strength metal and polished to specular reflectance on the inside surface, with the irradiable target placed in layer or like form at the bottom. The incidenting beam enters the bottle, to strike the target, with multiple internal reflections within said container routing the light back into the target.

I have found from laser experiments that an interesting and unique class of irradiable targets can be prepared by incorporating, as by simple mechanical admixture(with semi-fusion as a pretreatment to consolidated the mass, should this be feasible), particles of a more refractory(and unreactive) light absorptive solid with the less refractory(and reactive or energy-responsive) target phase(usually solid). The target material may be otherwise only slightly absorbent for the optical energy involved, e.g., white or very light in color. This hetereogenous system responds to the optoexplosion light involving absorption thereof by the darker substance which transfers its energy as thermal energy to the less-absorptive, lighter target material. After an irradiation the two may be separated by simple pulverization (the absorber particles, when hard and non-pulverizable under the conditions employed, are then simply screened out), by solution of the target material, by mechanical sorting, and the like. The same approach can be utilized in the case of liquid targets which are relatively non-absorptive; inert light-absorbing particles are mixed therewith, to transfer their energy to the liquid; in this instance the target medium should be withina container and under pressure(if not sealed), so that explosion and dissipation of the liquid does not result.

By the same token, for low input fluxes an otherwise transparent, colorless or non-absorptive(say for a particular wavelength) target material can have in solid or liquid solution an absorptive solute, e.g., black dyestuff.

Transparent and relatively non-absorptive target material of the solid kind(including frozen liquids and solified gases) can be first comminuted, so that the resulting mass comprises many particles each of which presents a fresnel-reflecting surface, thus to give multiple internal reflections; preferably the surface of such a mass is the unbroken, transparent substance itself.

I would include an "active target" as a form of irradiable target. Illustratively, this is target material which is say field-responsive(electrical or magnetic), and changes its optical properties upon the application thereto of energy. For example, many of the physical phenomena recited by George Raabe(cited hereinbefore), like the Kerr and Pockels effects, are adapted to active irradiable target modifications when, of course, the target material is a substance which shows the response in question. Thus, a so-called Kerr- or Pockels- active liquid or solid, upon energization, assumes an optical configuration wherein it will behave differently towards the polarized and unpolarized components which may make up light derived from an optoexplosion.

The irradiable target may be an optical transducer or amplifier. In the former it may be a phosphor or broad excitation spectrum comprising in a given instance unwanted wavelengths, to transduce these into wanted wavelengths which are optically coupled with a medium absorptive and responsive thereto. The large literature on luminescence need not be cited at this point, except to illustrate same by ultraviolet-emitting phosphors of high intensity output(cf. J.W. Gilliland et al., "Research and Development of Cathodoluminescent Phosphor with High-Intensity Ultraviolet Emission," CFSTI AD 657,589, 132 pp., 92 refs., 205 phosphors listed, June 1967; I would particularly point out for the artizan that a preponderance of cathodoluminescent phosphors can be excited by short wavelength ultraviolet to emit in Stokesian mode, also that this list contains substances(including pure materials) which emit in the vacuum ultraviolet, which is of especial interest in connection with the present invention as a "FUV-generator" (far or extreme ultraviolet, into the trans X-ray portion of the spectrum).

Like the phosphor transducer which is characterized by the emission of light, when the irradiable target is an amplifier like a laser a number of advtangeous features are the consequence. My original disclosure gives an extensive listing of laser media(for the time, 1964), and in the section herein on frangible reflective optics I set out an active FRO which includes lasing material. These, generally, include, solids (crystals and glasses), liquids, and gases tractable to optical pumping by optoexplosion light bounced from the FRO element. Various means like Q-switching, cooling, and the like can be utilized to shape the performance and output of the laser target which, in turn, is in optical communication with the end target of the series. Because it is often that such an arrangement of the present improvement with a laser is a one-shot affair, I prefer lasers which are low in cost and which can be worked and handled in relatively large bulks or volumes. For example, the Lempicke-type aprotic solutions of neodymium or other rare earths; plastic and glass laser resonators; and the like. Snitzer-glasses in fagot configuration(a bundle of rods) of glassified laser ions are especially good for high efficiencies, although many of these are limited to the infrared; the report of C.G. Young(Microwaves(Laser Technology Sectn.), 7(7), 69–78(July)1968) should be consulted for these data. I do not exclude, for example, gas and vapor laser resonators which, in the case of H_2O, D_2O and HCN, for example, are capable of lasing into the + 700 micron range.

I therefore include within the scope of this invention a chemical-explosive-pumped and/or a nuclear-explo-

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sive-pumped laser, consistent with what is disclosed and claimed in my parent application. The laser and its cooperant optics(e.g., retroreflective mirror lens(es), Q-switches) may be positioned in fixed or static attitude, or the laser ensemble can be movably mounted(e.g., 30*d* and 30*e* in FIGS. 5 and 4, respectively), so as to be translationally and/or rotationally mobile, as by gimbal support.

Another example of an irradiable target is tissue, live or dead, healthy or moribund. For simulated flashburn studies, to further knowledge of the various kinds and degrees of nuclear flashburn, the living animal model is the target. This model can be exposed to raw CAL or to raw CX source light. Or, should it be desired to program into the model situation a varying energy flux the techniques set out hereinbefore can be employed, as for example when it is necessary for whole body or, at least, large surface area, irradiation by light fluxes which vary in energy densities across their faces(e.g., depiction by simulant test of "shadowed" light exposures).

By definition an irradiable target includes photoresponsive devices. These may be sensors of the roughly categorized (a) electronic and (b) non-electronic varieties. Many light sensors and light recording devices and methods and means are well known. The choice of a particular sensor will usually depend upon the form this invention takes with reference to the purpose thereof, including a consideration of the light flux values and the region of the spectrum being worked, and such choices are well within the capability of those skilled in the art—other than to add that within the realm of ultrahigh power optical energies non-linear and intensity-dependent effects may well come into play(cf. A. Einstein, Physik Zeit., 18,122(1917); G. Bret and F. Gires, Compt. rend., 258,3469(1964); G. Bret and F. Gires, Appl. Phys. Lttrs., 4,175(1964); E.U. Condon, Proc. Natl. Acad. Sci.(U.S.),53(3), 635-637( )).

Auxilliary circuitry and the like may be chosen from the conventional art of electronics, according to sensor readout in terms of final signal; recording, image(including computer imaging and computer graphics and electronic image display, which methodologies form their respective states of the art), and the like.

The electronic and like sensors in my working distinction here include photocells(e.g., photoemissive, photoconductive, photovoltaic), thermopiles, thermistors, radiometers, bolometers, pyrometers, photomultiplier tubes, and the like. As indicated, the choice of a given sensor is decided by, among other things, the light flux, the spectral range involved, the relative intensities between the various lines and/or bands, and the adaptability to amplification or subsequent readout upon a machine like an oscilloscope, tracing machine, or strip recorder, and the like.

When degradation of the optoexplosion light(e.g., intensity) is involved, as by multiple reflections through a series of passes or by multiple refractions, or is beam-splitted, an image intensifier can be employed when the irradiance is low(as for example in monitoring diffusely-reflected or glossy-reflected light or fresnel-reflected light from a highly transparent optic) and/or when the light varies greatly through its time-intensity profile(as in the case of a low-flux leading edge and a low-flux trailing edge, with a median peak, in a sinusoid pulse).

The so-called non-electronic and like sensors and recorders include photosensitive chemical structures, as for example photographic emulsions, including: (a) halide, (b) non-halide, (c) black-and-white for the previous two, (d) spectrally specific or color for (a) and (b), also, (e) photochromic and thermochromic agents(as in screen form) and, as detailed herein (f) various luminescents including fluorescents, thermoluminescents, and infrared transducing phosphors(into anti-Stokesian luminescent light), and the like.

The luminescents can be incorporated with or adapted to emission-coupling with target medium by admixture with the latter. Or by solution therein. Thus, as described previously a luminescent transduces optical energy into a wavelength suitable for treating a target material. However, an quite conversely, a luminescent can act to preferentially and selectively absorb undesirable wavelengths so as to protect a coupled target medium from those wavelengths, with emission in inactive regions of the spectrum.

While I have shown and described the various preferred embodiments of my invention, it is to be understood that the drawings and detailed disclosure are to be construed in an illustrative sense since various versions, modifications and substitutions of equivalents may be made by those skilled in the art within the spirit and scope of this invention. I would again particularly emphasize and point out that in many instances close-in explosion phenomenology is little or scantly known because of the obvious working difficulties. This invention aims to overcome certain of these obstacles. At the same time I would venture to say that other than the raw optical effects of CX and NX explosions a great many gaps exist in close-in, sophisticated optical phenomena characteristic of substantial yield explosions—which phenomena are adapted to control, manipulation and utilization by proper approaches. Among those proper approaches is the feature and aim of this invention.

Hereinbefore I have endeavored to discern and point out certain of the gaps which from a methodology and fact basis seem either lacking in the art or to have been neglected, one reason I ascribe the state of the explosives art being the somewhat traditional and, therefore, rigidized view that explosives are chemical or nuclear workhorses pronounced by their kinetic energies. An aim and a feature of this improvement has been to demonstrate that explosives, especially when properly designed as molecules and formulations and physical shapes, possess great potential utility for what I have previously termed *optoexplosive technology*.

Finally: Although I have described my invention and its parent in detail—the disclosures of which interrelate and commingle—so as to complement and reinforce one another—and have specified numerous particular examples and various combinations, and have proposed various explanations, it is to be understood that these are not binding nor exchaustive. Rather, they are intended for the assistance of others skilled in the art to enable them more easily to apply my invention—together with the parent invention—under widely varying conditions encountered or desired in actual practice and to change and modify the particular embodiments and examples herein set out as may be necessary or desirable under such varying conditions.

The theoretical statements and explanations of working principles, which to my best understanding are correct, are of course not necessarily conclusive and my invention is in no way dependent upon their correctness, particularly in view of the absence of knowledge in the ultrahigh power optical energy domain. I have found them helpful and have based them wherever possible upon the best knowledge of the physical sciences(which knowledge I have extensively searched out in the literature) and give them for the aid of others, but my invention will be equally useful should it prove that these explanations and conclusions are not altogether correct.

I claim:

1. In combination with an irradiable target characterized as sensitive to the kinetic energies of an explosion, for the irradiation of said target with reflectable electromagnetic radiations, the system which comprises:

a. an enclosed main duct emplaced underground, said duct having two end parts;

b. a firable explosive positioned within a first end part of the said main duct, said explosive characterized as generating reflectable electromagnetic radiations and kinetic energies of different velocities;

c. a secondary, branching duct joined with the main duct between the two end parts;

d. a frangible reflective optic angularly sited within the main duct to reflect reflectable electromagnetic radiations into the said branching duct;

e. and an irradiable target reflectively coupled to the said frangible reflective optic through the branching duct; such that upon the firing of the said firable explosive reflectable electromagnetic radiations strike the frangible reflective optic and reflectively couple with the said irradiable target and the non-reflectable energy breaks through the said optic and deposits within the said second send part of the main duct, so that the target is irradiated.

2. The combination as set forth in claim 1, wherein the said firable explosive is a nuclear explosive.

3. The combination as set forth in claim 1, wherein the said firable explosive is a chemical explosive.

4. The combination as set forth in claim 1, wherein the said branching duct joined with the main duct between the two said end parts subtends by less than 90° in the direction of the said first end part of the main duct having positioned therein the firable explosive.

5. The combination as set forth in claim 4, wherein the said firable explosive is nuclear explosive.

6. In a branched underground tunnel system for nuclear explosive light generation a destructible reflective member optically coupled at a first angle with a nuclear explosive source of light and optically coupled at a second angle with a tunnel branching in communication with an irradiable target, the said second angle characterized as being different from the said first angle; and a receptable arranged at a third angle, said third angle characterized as being different from the said second angle, so that upon explosion of the said nuclear explosive source of light there is generated reflectable rays togethers with non-reflectable rays, the said reflectable rays having a velocity greater than the velocity of the said non-reflectable rays, such that the reflectable rays strike the reflective member before the non-reflectable rays and reflect at the first angle from the said member into the second angle and into the said irradiable target, and thereafter the non-reflectable rays strike the destructible reflective member to destroy the member with the non-reflectable rays and the debris from the destroyed member being carried into the said receptacle.

7. In a branched underground tunnel system for nuclear explosive light generation as set forth in claim 6, wherein the said second angle is approximately 90° with respect to the said first angle.

8. In a branched underground tunnel system for nuclear explosive light generation as set forth in claim 6, wherein the said second angle is less than 90° with respect to the said first angle.

9. In a branched underground tunnel system for nuclear explosive light generation as set forth in claim 6, wherein the said second angle is more than 90° with respect to the said first angle.

10. In a branched underground tunnel system for nuclear explosive light generation as set forth in claim 6, wherein a single nuclear explosive source of light at a common first angle is optically coupled with at least two of the said second angle tunnel branchings.

11. An underground nuclear device for the separation of the reflectable electromagnetic radiation from the non-reflectable energy of a contained nuclear explosion, wherein the said reflectable electromagnetic radiation has a velocity greater than that of the non-reflectable energy, which comprises:

a. a substantially straight containment tunnel underground;

b. at least one side-arm duct joining the said tunnel at a right angle between the closed ends of the said tunnel;

c. a nuclear explosive device set at one of the ends of the tunnel, said nuclear device characterized as generating reflectable electromagnetic radiation together with non-reflectable energy of faster and slower velocities;

d. actuation means for the firing of the said nuclear device;

e. a frangible reflective optic at the said joining of the tunnel and the side-arm duct, said optic being in a common coupling with the tunnel and the side-arm duct at approximately one-half of a right angle with respect to the tunnel and the duct;

f. an irradiable target sited within the said side-arm duct adapted to receive the said reflectable electromagnetic radiation from the said optic moving faster than the said non-reflectable energy;

g. and a second end receptacle part of the said tunnel adapted to depose of the slower non-reflectable energy from the explosion of the nuclear device.

12. An underground optoexplosive device for the separation of the reflectable electromagnetic radiation from the non-reflectable energy of a contained explosion, wherein the said reflectable electromagnetic radiation is characterized as having a velocity greater than the said non-reflectable energy of the explosion, which comprises:

a. a substantially linear tunnel situated underground, said tunnel having two ends at least one of which ends is closed;

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b. an explosive energy source contained within the said tunnel at one of the said ends;
c. explosive energy source firing means in communication with the said explosive energy source;
d. at least one first side-arm duct having a closed end, the said first duct joining the said tunnel between the ends thereof at an angle less than a right angle in the direction of the end of the tunnel containing the said explosive energy source;
e. at least one second side-arm duct angularly joining the first side-arm duct between the closed end and the first joining thereof;
f. a series of frangible reflective optics positioned at an angle at the joinings of the said tunnel and the said side-arm ducts, said angle adapted to the common axes of the tunnel and the ducts;
g. an irradiable target optically coupled to the said series of frangible reflective optics through the ducts and tunnel;
h. and closed end portions of the tunnel and ducts adapted to receive the said non-reflectable energy from the explosion of the explosive source upon the firing thereof.

13. An underground optoexplosive device as set forth in claim 12, wherein the said first side-arm duct is sealed off underground and the said irradiable target carried within the said second side-arm duct is sealed off therein.

14. An underground optoexplosive system as set forth in claim 12, wherein the said explosive energy source is a nuclear explosive device.

15. An underground optoexplosive device as set forth in claim 12, wherein the said explosive energy source is a chemical explosive device.

16. An underground explotron for the separation of the faster moving reflectable electromagnetic radiation from the slower moving non-reflectable energy of an explosion, for the treatment of an irradiable target with refelectable radiation, the system which comprises:
a. an underground main tunnel having closed ends;
b. a firable explosive device positioned within the said main tunnel between the said closed ends;
c. at least two branching pipes joining the said main tunnel between the closed ends and on each side of the said explosive device;
d. an angular conjoinment of the ends opposite the closed ends of the said pipes so as to form a common chamber;
e. at least two frangible reflective optics emplaced at the joinings of the said pipes and the main tunnel, such that there is an optical coupling of the said explosive device with the said common chamber through the main tunnel and pipes;
f. and an irradiable target in optical communication with the common chamber; such that upon firing the said firable explosive device the faster moving reflectable electromagnetic radiation first reflects into the irradiable target and the slower moving non-reflectable energy breaks through the said frangible reflective optic and passes into the closed ends of the main tunnel.

17. The underground explotron as set forth in claim 16, wherein the firable explosive device includes a chemical explosive agent.

18. The underground explotron as set forth in claim 16, wherein the firable explosive device includes a nuclear explosive agent.

19. The combination in an underground optoexplosive system for the time controlled treatment of an irradiable target with explosion energy which comprises:
a. a main tunnel section positioned underground;
b. a firable explosion energy source sited within the said main tunnel section including a branching upper leg and a branching lower leg, the said legs being conduits and branching in a substantially common axis with respect to one another from the site of the said explosion energy source sited within the tunnel;
c. a controllably impellable piston movably emplaced within the said upper leg;
d. a passageway for the piston in the upper leg through the site of the explosion energy source;
e. a lower leg adapted to receive the said impellable piston upon movement from the upper leg and the traversing thereof of the said passageway in the tunnel section containing the explosion energy source;
f. and means for the time controlled release of the piston in the upper leg;
such that upon the firing of the explosion energy source into a live explosion the release of the said piston and its traversing of the said site diverts a part of the explosion into the said lower leg while the non-diverted part of the explosion enters the main tunnel section.

20. The combination of an underground optoexplosive system for the time controlled treatment of an irradiable target with explosion energy as set forth in claim 19, wherein the release of the piston is by mechanical release.

21. The combination of an underground optoexplosive system for the time controlled treatment of an irradiable target with explosion energy as set forth in claim 19, wherein the release of the piston includes the application of explosive force to the piston.

22. The combination in an underground optoexplosive system for the time controlled treatment of an irradiable target with explosion energy which comprises:
a. a main tunnel section positioned underground;
b. a firable explosion energy source sited within the said main tunnel section including a branching upper leg and a branching lower leg, the said legs being conduits and branching in a substantially common axis with respect to one another from the site of the said explosion energy source sited within the tunnel;
c. a secondary source of explosion energy firably emplaced within the said upper leg;
d. a passageway between the site of the said firable explosion energy source in the main tunnel section and the said upper leg;
e. a lower leg adapted to receive energy from the said secondary source of explosion energy firably emplaced within the said upper leg;
f. and means for the time controlled firing of the said secondary explosion energy source;
such that upon the firing of the firable explosion energy source into a live explosion the release of energy from the said secondary source traverses the site of the firable explosion energy source and diverts a part of the explosion thereof into the lower leg while the non-diverted part of the explosion enters the main tunnel section.

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23. The combination in an underground optoexplosive system for the time controlled treatment of an irradiable target with explosion energy as set forth in claim 22, wherein the said secondary source of explosion energy is a shaped charge.

24. The combination in an underground optoexplosive system for the time controlled treatment of an irradiable target with explosion energy as set forth in claim 22, wherein the said secondary source of explosion energy includes chemical explosive.

25. The combination in an underground optoexplosive system for the time-controlled treatment of an irradiable target with explosion energy as set forth in claim 22, wherein the said secondary source of explosion energy includes nuclear explosive.

* * * * *

United States Patent [19]

Viecelli

[11] **3,813,555**

[45] **May 28, 1974**

[54] **METHOD AND MEANS FOR PRODUCING COHERENT X-RAY AND GAMMA-RAY EMISSIONS**

[75] Inventor: **James A. Viecelli, Oakland, Calif.**

[73] Assignee: **The United States of America as represented by the United States Atomic Energy Commission,** Washington, D.C.

[22] Filed: **May 16, 1973**

[21] Appl. No.: **360,983**

[52] U.S. Cl. **250/493,** 250/495

[51] **Int. Cl.** **H01j 35/00**

[58] **Field of Search** 250/493, 494, 495; 331/94.5

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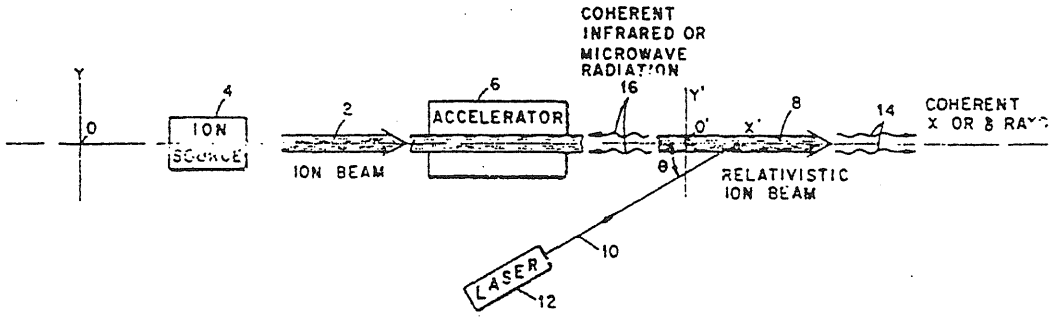
Primary Examiner—James W. Lawrence
Assistant Examiner—B. C. Anderson
Attorney, Agent, or Firm—John A. Horan; F. A. Robertson; L. E. Carnahan

[57] **ABSTRACT**

A method and apparatus for producing coherent x-ray and gamma-ray emissions by taking advantage of doppler shift phenomena and the relativistic effects of time dilation, wave vector angle compression, and length compression associated with an active optical lasing medium moving at a uniform velocity very nearly equal to the speed of light.

7 Claims, 2 Drawing Figures



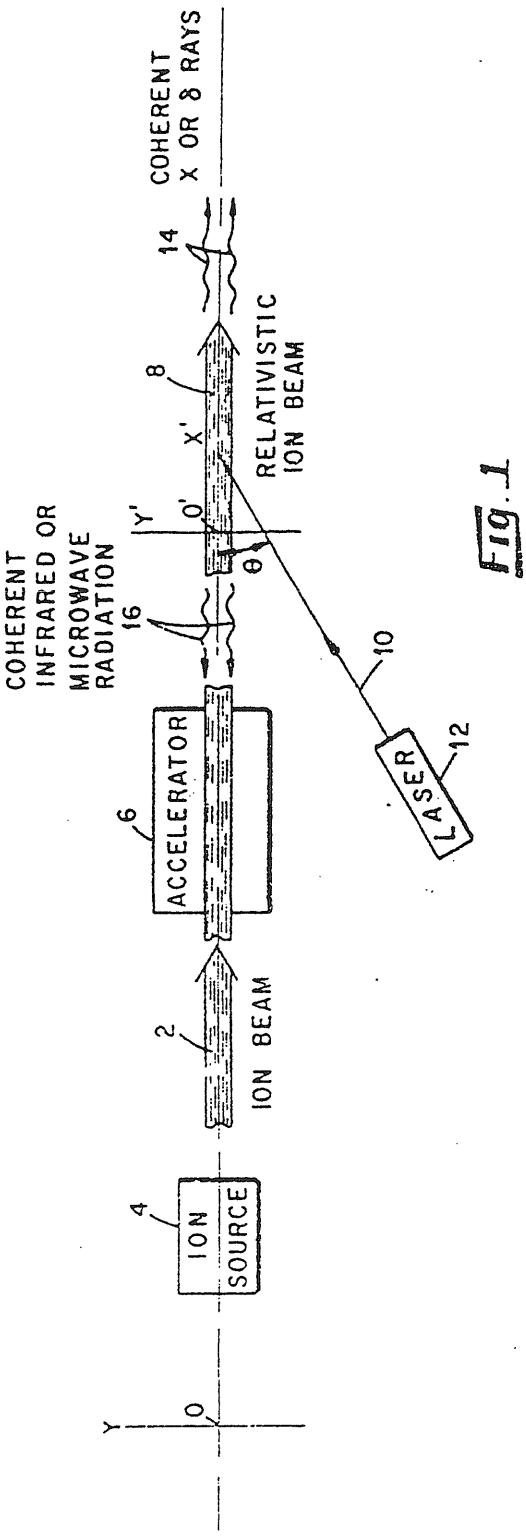

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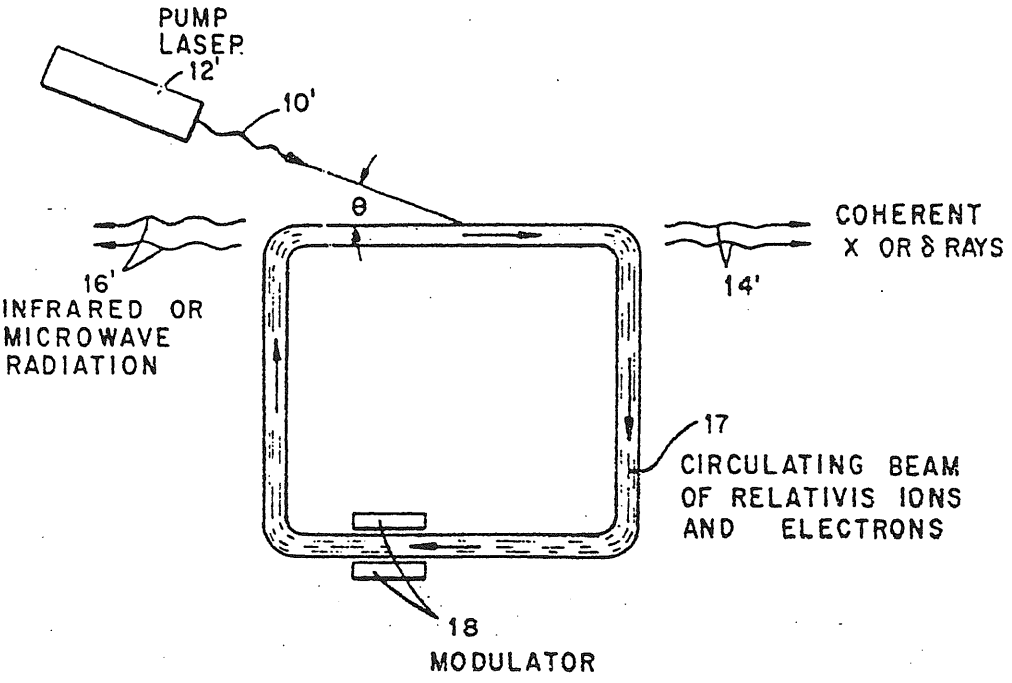
Fig. 1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OF RELATIVIS IONS
AND ELECTRONS
18
MODULATOR

Fig. 2

METHOD AND MEANS FOR PRODUCING COHERENT X-RAY AND GAMMA-RAY EMISSIONS

BACKGROUND OF THE INVENTION

The invention described herein was made in the course of, or under, Contract No. W-7405-ENG-48, with the U.S. Atomic Energy Commission.

The highest coherent radiation (laser) frequencies which can be produced by presently known techniques and devices are in the ultraviolet frequency region. As is well known to those skilled in the art, coherent radiation frequencies extending into the x-ray and gamma-ray regions would be very useful in such fields as communications and laser fusion.

SUMMARY OF THE INVENTION

The present invention provides a method and apparatus for producing coherent x-ray and gamma-ray emissions, and involves: 1. generating an ion beam which can be induced into laser action to cause the emission of a beam of coherent radiation having a characteristic frequency; 2. accelerating the ion beam to a relativistic velocity with respect to a stationary reference point; and 3. inducing laser action in the accelerated ion beam, to thereby cause the emission of a beam of coherent radiation having a frequency much greater than the characteristic frequency when measured with respect to the stationary reference point.

With suitable values for the characteristic frequency and the relativistic velocity, beams of coherent radiation may be produced which have frequency values within the x-ray and gamma-ray range of the electromagnetic frequency spectrum.

It is therefore the principal object of the present invention to provide a method and means for producing coherent x-ray and gamma-ray emissions.

Other objects of the invention will become apparent from the following description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 schematically illustrates a basic embodiment of an apparatus in accordance with the invention; and

FIG. 2 schematically illustrates an embodiment of the invention utilizing a circulating beam.

DESCRIPTION OF THE INVENTION

Briefly, the invention is achieved by taking advantage of doppler shift phenomena and the relativistic effects of time dilation, wave vector angle compression, and length compression associated with an active optical lasing medium moving at a uniform velocity very nearly equal to the speed of light.

The ions of many elements and their compounds can form a gaseous medium which may be induced into laser action by an optical pumping beam to cause the emission of coherent radiation having a frequency value characteristic of the type of ion in the medium.

In the basic embodiment of the invention, shown in FIG. 1, such a medium is generated in the form of an ion beam 2 by an ion source 4. The beam 2 as a whole is accelerated, such as by means of a superconductor microwave accelerator 6, to an ion beam 8 having a

predetermined uniform velocity approaching the speed of light with respect to an observer 0 at rest in a "laboratory" reference frame XY. An optical pumping beam 10 from a source 12, such as a conventional laser, is passed through the relativistic ion beam 8 at a predetermined angle Θ with respect to the reference frame XY such as to establish the necessary conditions for laser action, i.e., stimulated emission of coherent radiation, in the ion beam medium.

When laser action occurs, an observer 0' at rest in a reference frame X'Y', moving with the relativistic ion beam 8, will detect two beams of coherent radiation 14 and 16 having the same frequency value ν' characteristic of the ionic beam material, beam 14 traveling in the same direction as the ion beam 8 (the "forward" direction) with beam 16 traveling opposite to the direction of ion beam 8 (the "backward" direction). To the observer 0, however, the frequency of coherent beam 14 will be much greater than ν' and the frequency of coherent beam 16 will be much less than ν', due to doppler shift phenomena and relativistic effects.

As described in more detail below, it is this difference in the detected frequency of coherent beam 14 by observers 0 and 0' which is used to achieve the production of coherent x-ray and gamma-ray emissions.

Assume that, relative to observer 0, ion beam 8 has a velocity $V=(1-\epsilon)c$, where c is the speed of light, and $\epsilon<<<1$. Then the transformation properties of the special theory of relativity for radiation in the XY and X'Y' frames of reference show the following effects and results.

1. The frequency of the "forward" coherent beam 14, as detected by observer 0, will be

$$\nu=\sqrt{2/\epsilon}\,\nu'$$

As an example, let $\epsilon=2\times10^{-6}$. Then $\nu=1000\nu'$. Thus, to the observer 0, the frequency of the emitted coherent radiation beam 14 is 1,000 times the characteristic frequency ν' of the lasing medium of the relativistic ion beam 8. If ν' is selected to be in the visible region of the spectrum, then ν will be in the x-ray frequency range. Similarly, still smaller values for ϵ will give values for ν in the gamma-ray frequency range.

2. The relationship between an angle θ' in the X'Y' frame and the corresponding angle θ in the XY frame is highly nonlinear. Assume that observer 0' measures the angular spread of the "forward" coherent beam 14 as $\delta\theta'$. The observer 0 will measure the angular spread as:

$$\Delta\theta=\sqrt{\epsilon/2}\,\delta\theta'$$

As an example, let $\epsilon=2\times10^{-6}$. Then $\Delta\theta=0.001\,\delta\theta'$. Thus, the "forward"coherent beam 14 is much more directional to observer 0 than to observer 0'.

3. The relationships between angles and between frequency and angles show that for a suitable choice of the incident angle θ of the optical pumping beam 10, it is possible to have the frequency of the optical beam 10 appear the same to both observer 0 and 0'. For example, for $\epsilon=2\times10^{-6}$, the frequency of the optical pumping beam is the same to both observer 0 and 0' if the angle of incidence θ is 3°37'. Thus, from the point of view of observer 0, the optical pumping beam 10 must be aimed nearly parallel to the ion beam direction. However, to the observer 0', the optical pumping beam 10 would appear to be coming from almost dead

ahead, i.e., with an angle of incidence θ of 176°23'. As an alternative, the angle of incidence of the optical pumping beam 10 can be adjusted such that the frequency of beam 10 as detected by observer 0' is greater than the frequency of beam 10 as detected by observer 0. Thus, by suitable choice of the angle of incidence of beam 10, the relativistic ion beam medium can be excited at x-ray or ultraviolet frequencies in the X'Y' frame using visible light frequencies in the XY frame.

4. Assume that observer 0' determined that an ion density n_o' is required in the ion beam 8 to get gain. Then to observer 0 the corresponding ion density n_o will be much greater, i.e.:

$$n_o = 1/\sqrt{2\epsilon}\, n_o'$$

In summary, observer 0', traveling with the relativistic ion beam 8, will detect equal amounts of coherent radiation emitted in the "forward" and "backward" direction (beams 14 and 16). With suitable choices for ϵ and ν', observer 0, at rest in the laboratory frame, will detect coherent x-rays or gamma-rays (beam 14) traveling in the "forward" direction, and coherent infrared or microwave radiation (beam 16) traveling in the "backward" direction. However, because of the relationship between angles in the frames XY and X'Y', the divergence of coherent beam 16 is much greater than that of beam 14.

Although the number of photons emitted in the forward and backward directions is the same relative to observer 0, almost all of the energy and momentum of the generated coherent radiation will come out in the forward direction because of the large difference in frequency between beams 14 and 16. The energy for the x-ray or gamma-ray beam 14 comes from the directed kinetic energy of the relativistic ion beam 8.

By way of example only, to illustrate the invention, the ion beam 2 is generated by ion source 4 from material, for example, such as: argon (Ar), krypton (Kr), xenon (Xe), neon (Ne), mercury (Hg), oxygen (O), boron (B), carbon (C), and cadmium (Cd). Laser oscillations or amplification has been obtained in the visible or near ultraviolet for the ions of these materials and many others. High power outputs have been obtained at 5,145 A and 4,880 A in Ar II and at 4,416 A and 3,250 A in Cd II. Using cadmium with a value $\epsilon = 2 \times 10^{-6}$ (example discussed earlier) the wavelength of beam 14 would be 4.416 A for the 4416 A transition and 3.250 A for the 3250 A transition. The corresponding wavelengths for beam 16 would be 0.4416 millimeters and 0.3250 millimeters. To pump the Cd II laser levels frequencies of 74,894 cm^{-1} and 69,259 cm^{-1} are required in the beam frame. If a ruby laser is used as the pump (6940 A) then the required angles in the lab frame (θ) are 8° 16' and 7° 57'. Other kinds of lasers such as Nd:YAG or CO_2 can also be used for the pump, but then the angle (θ) must be altered so that one still obtains 74,894 cm^{-1} or 69,259 cm^{-1} for the pump frequency in the beam frame (for the Cd II example). The formula for the angle θ is

ν (pump frequency in beam frame)/$\nu\nu$ (pump frequency in lab frame) $\sqrt{1-(V^2/C} = 1 - v/C \cos\theta$

v = Beam velocity

C = velocity of light.

The system can operate without feedback, in which case beam 14 is produced by amplification and gain narrowing of spontaneous emission in the direction of the beam. Alternatively, feedback can be provided so that the device acts as an oscillator. Feedback can be distributed throughout the beam 8 by spatially modulating the number density of the ions as they pass through the accelerator 6. If L is the period of the spatial modulation then the wavelength of oscillation in the beam frame is approximately 2L. For the Cd II example one would need L=2,208 A or 1,625 A, (in the beam frame).

It should be noted that no existing heavy ion accelerators are capable of approaching the energies required for $\epsilon << 1$, but perhaps in the future they will be. The ion velocities that can be obtained with existing machines are only a small fraction of the speed of light. The principle of the invention still applies, but the frequency shifts obtained are small.

The highest energy achieved so far is 30 Mev with He ions. There are development efforts contemplating energies in the 1,000 Mev range. These are based on the collective acceleration of ions and electrons. With the cadmium example at 1,000 Mev the doppler shift would only be 14 percent corresponding to wavelengths of 3,870 A and 2,840 A for beam 14.

FIG. 2 illustrates an embodiment of the invention utilizing a circulating beam of relativistic ions and electrons from an ion source passed through an accelerator (not shown but similar to that of FIG. 1), the beam being bent or deflected by beam deflecting apparatus not shown but which, for example, may be electromagnetic mechanism known in the art. Like components of the FIG. 1 embodiment will be given like reference numerals. As shown, a circulating beam of relativistic ions and electrons indicated at 17 pass through a modulator 18 which spatially modulates the density of the ions at a wavelength (in the beam frame) equal to ½ the wavelength of the laser transition of the ions. As the beam 17 circulates an optical pumping beam 10' from a source such as laser 12' is passed through the ion beam 17 at a predetermined angle θ with respect to the reference frame XY as in the FIG. 1 embodiment, whereby two beams of coherent radiation 14' and 16' travelling in opposite directions are detected as described above with respect to FIG. 1.

The method and apparatus of the invention described above attempt to avoid the apparently fundamental high frequency limit on laser operation imposed by the Einstein relationship between the spontaneous emission and stimulated emission coefficients ($A \alpha \nu^3 B$). This is accomplished by arranging for the laser action to take place in a coordinate frame (X'Y') where the spontaneous/stimulated ratio (A/B) is favorable, while having the emitted coherent radiation, the optical pumping beam, and the energy supply (the ion accelerator) in a different coordinate frame (XY).

It has thus been shown that the present invention provides a method and apparatus which involves:

1. Generating an ion beam which can be induced into laser action to cause the emission of a beam of coherent radiation having a characteristic frequency.
2. Accelerating the ion beam to a relativistic velocity with respect to a stationary reference point.
3. Inducing laser action in the accelerated ion beam, to thereby cause the emission of a beam of coherent radiation having a frequency much greater than

the characteristic frequency when measured with respect to the stationary reference point.

Thus, with suitable values for the characteristic frequency and the relativistic velocity, beams of coherent radiation may be produced which have frequency values within the x-ray and gamma-ray range of the electromagnetic frequency spectrum.

While a particular embodiment for carrying out the method and particular examples have been illustrated and described, modifications and changes will become apparent to those skilled in this art, and it is intended to cover in the appended claims all such modifications and changes as come within the spirit and scope of the invention.

What I claim is:

1. A method for producing coherent x-ray and gamma-ray emissions comprising the steps of: generating an ion beam which can be induced into laser action to cause the emission of a beam of coherent radiation having a characteristic frequency; accelerating the ion beam to a relativistic velocity with respect to a stationary reference point; and inducing laser action in the accelerated ion beam by directing an optical pumping beam through the accelerated ion beam at an angle θ with respect to a fixed reference frame, said angle θ being defined by the formula: ν (pump frequency in beam frame)/ν (pump frequency in lab frame) $\times \sqrt{1-V^2/C} = 1 - V/C \cos\theta$ where V = beam velocity and C = velocity of light causing the emission of a beam of coherent radiation having a frequency greater than the characteristic frequency when measured with respect to the stationary reference point.

2. The method defined in claim 1, wherein said step of accelerating the ion beam is accomplished by directing the beam through a superconductor microwave accelerator.

3. The method defined in claim 1, wherein said step of directing an optical pumping beam through the accelerated ion beam is carried out by passing a laser beam through the ion beam at an angle θ with respect to a fixed reference frame, said angle θ being defined by the formula: ν (pump frequency in beam frame)/ν (pump frequency in lab frame) $\sqrt{1-\nu^2/C} = 1 - \nu/C \cos\theta$ where ν = beam velocity and C = velocity of light.

4. An apparatus for producing coherent x-ray and gamma-ray emissions comprising: means for producing an ion beam of medium capable of being induced into laser action; means for accelerating the ion beam to a uniform velocity approaching the speed of light with respect to a stationary reference frame, means for inducing laser action in the accelerated ion beam, thereby causing emission of a beam of coherent radiation having a frequency greater than the characteristic frequency of the ion beam material when measured with respect to the stationary reference frame, said laser action inducing means comprising means for producing an optical pump beam and directing same through the accelerated ion beam at an angle θ with respect to the stationary reference frame, said angle θ being defined by the formula: ν (pump frequency in beam frame)/ν (pump frequency in lab frame) $\sqrt{1-\nu^2/C} = 1 - \nu/C \cos\theta$ where ν = beam velocity and C = velocity of light.

5. The apparatus defined in claim 4, wherein said medium is selected from the group consisting of argon, krypton, xenon, neon, mercury, oxygen, boron, carbon, and cadmium.

6. The apparatus defined in claim 4, wherein said accelerating means comprises a superconductor microwave accelerator.

7. The apparatus defined in claim 4, wherein said optical pumping beam producing means comprises a laser.

* * * * *

United States Patent [19]

Wood

[11] **3,823,325**

[45] **July 9, 1974**

[54] **X-RAY LASER**

[75] Inventor: **Lowell L. Wood, Simi, Calif.**

[73] Assignee: **The United States of America as represented by the United States Atomic Energy Commission, Washington, D.C.**

[22] Filed: **July 23, 1973**

[21] Appl. No.: **381,631**

[52] **U.S. Cl.** **250/493, 331/94.5**
[51] **Int. Cl.** **G03b 41/16**
[58] **Field of Search** 250/503; 331/94.5

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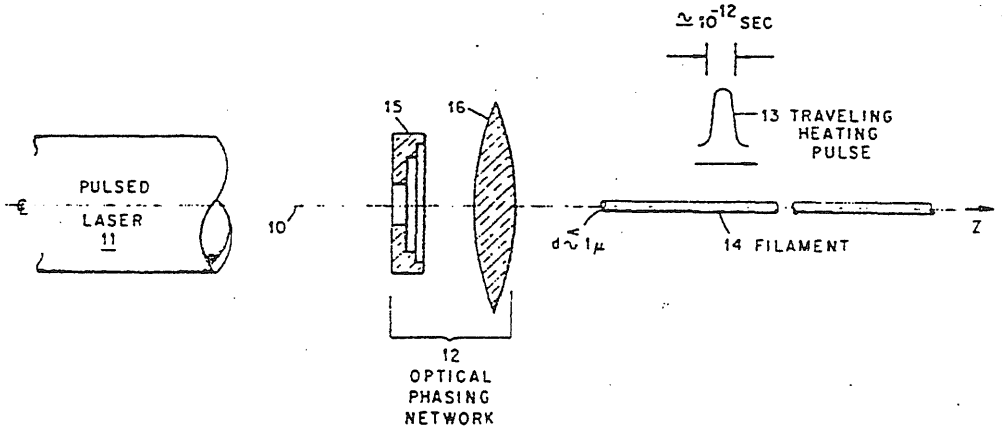
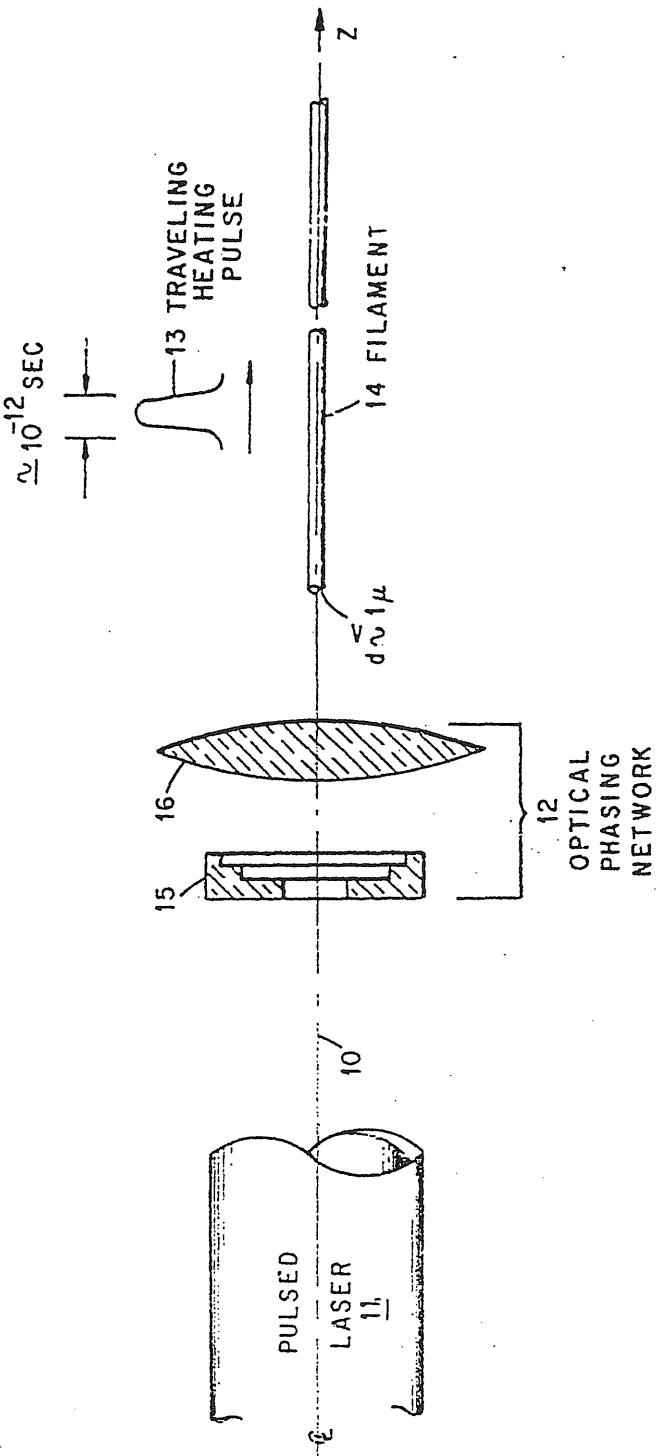
Primary Examiner—James W. Lawrence
Assistant Examiner—C. E. Church
Attorney, Agent, or Firm—John A. Horan; F. A. Robertson; L. E. Carnahan

[57] ABSTRACT

An x-ray laser utilizing rapid flash heating of a filament of intermediate Z material to temperatures of the order of the K-shell binding energy of the material.

6 Claims, 1 Drawing Figure




Z
13 TRAVELING HEATING PULSE
$\simeq 10^{-12}$ SEC
14 FILAMENT
$d \simeq 1\mu$
16
15
12 OPTICAL PHASING NETWORK
10
PULSED LASER 11

X-RAY LASER

BACKGROUND OF THE INVENTION

The invention described herein was made in the course of, or under, Contract No. W-7405-ENG-48. with the United States Atomic Energy Commission.

This invention relates to laser systems, and more particularly to an x-ray laser using flash heated medium.

Methods have been previously proposed to produce an x-ray laser system. These prior methods generally require unrealistically great time to establish alleged level population inversion, or develop population inversions in media which would show net negative gain, due to photoelectric losses, for example.

Because spontaneous emission is proportional to the third power of the frequency, extension of laser operations to high frequencies becomes increasingly more difficult. Noting a typical transition probability $\approx 10^9$ sec^{-1} for a 10 ev transition in the ultraviolet (≈ 0.1 μm), the transition probability for 100 ev x-rays is $\approx 10^{11}$ sec^{-1}. Hence, x-ray level population inversion must be established in $\leq 10^{-11}$ sec for x-ray ≤ 100 ev.

SUMMARY OF THE INVENTION

The present invention provides an x-ray laser based on the rapid ($\leq 10^{-12}$ sec) flash-heating of a filament of intermediate Z ($Z>2$ and <30) material to temperatures of the order of the K-shell binding energy of the material.

Therefore, it is an object of the invention to provide an x-ray laser.

A further object of the invention is to provide an x-ray laser using flash-heated medium.

Another object of the invention is to provide an x-ray laser based on the rapid flash-heating of a filament of intermediate Z material.

Other objects of the invention, will become readily apparent from the following description and accompanying drawing.

BRIEF DESCRIPTION OF THE DRAWING

The single FIGURE schematically illustrates an embodiment of an x-ray laser made in accordance with the invention.

DESCRIPTION OF THE INVENTION

The present invention is directed to an x-ray laser based on the rapid ($\leq 10^{-12}$ sec) flash heating of a filament of intermediate Z ($Z>2$ and <30) material to temperatures (1–10 Kev) of the order of the K-shell binding energy of the material.

As pointed out above, the spontaneous emission rate is proportional to the second power of the frequency, and thus extension of laser operations to higher frequencies becomes increasingly difficult. Also, as pointed out above, the transition probability for 100 ev x-rays is $\approx 10^{11}$ sec^{-1}, based on the typical transition probability $\approx 10^9$ sec^{-1} for a 10 ev transition in the ultraviolet (≈ 0.1 μm). Hence, x-ray level population inversion must be established in $\leq 10^{-11}$ sec for x-ray 24 100 ev.

This invention uses an ultra short pulse of laser radiation ($\leq 10^{-12}$ sec) to produce the population inversion by flash-heating, and subsequent radial expansion in a fine wire or filament (≤ 1 μm diameter). Lasing is accomplished by causing the heating, subsequently population inverting pulse to proceed along the wire (filament) with the group velocity of light in the expanding material; the x-ray amplifying, inversion-destroying de-excitations are thereby induced to proceed in phase with the heating pulse down the length of the wire. The population inversion develops transiently because the multi-body (predominantly three-body) processes in the dense, hydrodynamically cooling electron gas populate the upper bound states of the initially hydrogenic (essentially completely ionized) ions faster than the (mostly) radiative processes (two-body in nature) populate the lower bound states. Use of an appropriate heating pulse and a hollow (tubular) fiber may be made to result in radial implosion of the fiber to densities two to three orders of magnitude in excess of solid densities, further concentrating the heating pulse energy in space and time and permitting the attainment of population inversions in higher Z elements than would be possible without implosion. This advantage occurs because the imploded, highly compressed material is hydrodynamically heated and chilled much more rapidly in the imploded configuration than is attainable in any non-imploded one, permitting population inversions to be developed through collisional recombination in spite of faster radiative recombination processes in higher Z elements.

An embodiment of the x-ray laser system is illustrated in the drawing. The optical path length for a radiation beam 10 from a pulsed laser 11 is adjusted by an optical phase delay network, generally indicated at 12, so that a traveling wave heating pulse 13 passes along an x-ray lasing medium such as a filament or wire 14 (in direction of positive z axis) of an intermediate Z material at the group velocity of the x-radiation through the heated material of filament 14. The traveling wave heating pulse 14 has a width of $\leq 10^{-12}$ sec, with the filament 14 having a diameter of ≤ 1 μm and a length of 1 mm or more. For example, the filament 14 may be made of solid density fibers such as aluminum (Al) having a Z of 13 or titanium (Ti) having a Z of 22, or of imploded, hollow fibers such as iron (Fe) having a Z of 26 or copper (Cu) having a Z of 29. The pulsed laser 11 may be of the gas, chemical or other type capable of producing a $\leq 10^{-12}$ sec pulse. (Approximately $\leq 10^{12}$ watts $- \leq 1$ joule in $\leq 10^{-12}$ sec). The optical phasing network 12 consists of a corrector plate 15 and a lens 16. Network 12 satisfies simultaneously (a) group velocity heating criterion, and (b) requirement of equal heating per unit length.

It is extremely difficult to accurately estimate the populations of various levels as a function of time in the face of many complex and usually quite non-linear phenomena; the hydrodynamics of the situation alone precludes quantitative analytic treatment. For this reason the use of complex digital computer simulation efforts have been resorted to. The computer efforts have shown that 100 ev population inversion systems appear to be readily practicable since picosecond pump (flash-heating) laser sources are presently available. 1 kev population inversions involving allowed transitions are not currently obtainable in the sub-picosecond (10^{-13}) time scale, as pumping sources having such characteristic times are currently not available. Should $\leq 10^{-13}$ sec pump sources become available, population inversions may be created and utilized between electromagnetically connected levels in high Z plasmas, such that

the photon connecting the levels has energy of the order of 1 kev.

The particular physical systems thus modelled in the computer simulation efforts, and illustrated in the drawing, have been effectively right circular cylinders of intermediate Z metal, initially at normal density and effectively zero temperature. Their electron temperature and density histories were followed on a hydrodynamics and energy flow code as functions of radius and time as they are flash heated.

These temperature and density histories are then imputted to an isotropic, infinite medium simulation which computes bound electron shell populations in the average atom approximation, in the presence of a specified multigroup radiation field, taking into account free-free, bound-free and bound-bound radiation emission and absorption, and collisional excitation, ionization and recombination. The average atom approximation was believed to have been conservative, as most or all of the levels of a given shell must be superpopulated or underpopulated for an inversion of one shell relative to another to develop; inversion which might develop between particular levels of two shells were thus not counted.

The plasmas were transversely thin to their own radiation, except at the line centers, and the ambient radiation field was thus always specified to have no radiation in it; photons inputted to the radiation field by electrons becoming ever more tightly bound to ions were ejected from the simulations at the end of each very short simulation time step.

With picosecond-scale flash heating of aluminum fibers, inversions of the m-shell with respect to the *l*-shell have been seen in such simulations; similar inversions were seen for titanium fibers flash heated at higher rates and densities.

Since sound velocities are of the order of micron per picosecond at the appropriate electron temperatures for these cases of a few kilovolt temperatures, the initial diameters of these metal fibers were chosen to be of the order of a micron; the corresponding heat capacities were of the order of 10 joules/cm length of the fiber. Even taking into account the collisional and possible Stark broadening of the transitions of interest, lengths of considerably less than 1 cm were sufficient to achieve gains in excess of 100dB, more than sufficient to obtain superradiant axial pulses. Thus, the higher the inversion density can be made to be at a constant gain linewidth, the shorter the fiber must be to obtain a given axial gain.

The lasers are essentially four-level ones, in which the collisionally — and Stark-lowered continuum and the highly excited states are collectively the upper-most level, the *m*-shell is the upper lasing level, the *l*-shell is the lower one, and the lowest level is the *k*-shell, the sink into which the *l*-shell electrons dump after (possibly stimulated) transitions from the m and higher shells. It is when the small *k*-shell fills, and the *l*-shell "chokes up", that the system becomes a three level one and soon ceases to lase. The short radiative lifetime of the lower laser level relative to that of the upper level is of course primarily responsible for the creation and maintenance of the population inversion.

Transient population inversions between shells higher than the (*m,l*) pair have also been noted, but (*l,k*) inversions have not; the reasons for both of these are believed clear from the above discussion.

It is thus relatively straightforward to create population inversions involving photons of several hundred ev with present technological means; inversions of kilovolt energies are currently not obtainable, except through employment of energy-concentrating means, such as radial implosions.

It has thus been shown that the present invention provides an x-ray laser based on the rapid (10^{-12} sec) flash heating of a filament of intermediate Z material to temperatures of the order of the *k*-shell binding energy of the material, thus providing a significant advancement in the art.

While a particular embodiment of the invention has been illustrated and described, modifications will become apparent to those skilled in the art, and it is intended to cover in the appended claims all such modifications as come within the spirit and scope of the invention.

What is claimed is:

1. An x-ray laser utilizing flash-heating of a lasing medium to temperatures of the order of the K-shell binding energy of the medium comprising: means for producing a beam of laser radiation having a pulse of up to about 10^{-12} seconds, a longitudinally extending lasing medium of material having a diameter of up to about 1 micron and a Z in the range between 2 and 30 and an optical phasing network positioned intermediate said radiation producing means and said lasing medium, said lasing medium being axially aligned with said beam of radiation such that said beam produces flash-heating of said lasing medium producing a traveling heat pulse passing longitudinally along the lasing medium at the group velocity of x-radiation through the heated lasing medium causing a population inversion and lasing of the material.

2. The x-ray laser defined in claim 1, wherein said means for producing a beam of radiation comprises a pulsed laser.

3. The x-ray laser defined in claim 1, wherein said lasing medium comprises a metallic filament.

4. The x-ray laser defined in claim 3, wherein said filament is selected from the group consisting of aluminum, titanium, iron, and copper.

5. The x-ray laser defined in claim 1, wherein said optical phasing network comprises a corrector plate and a lens.

6. The x-ray laser defined in claim 1, wherein said lasing medium comprises a filament configured as a hollow fiber which the heating pulse causes to radially implode to high density and temperature prior to subsequent hydrodynamic relaxation and population inversion creation, so as to be able to further concentrate the energy of the heating pulse in space and time and afford the creation of population inversions in elements of higher Z thus allowing x-ray laser action involving more energetic photons to be produced.

* * * * *

United States Patent [19]

Mallozzi et al.

[11] **4,058,486**

[45] **Nov. 15, 1977**

[54] **PRODUCING X-RAYS**

[75] Inventors: **Philip J. Mallozzi; Harold M. Epstein; Richard G. Jung; David C. Applebaum; Barry P. Fairand,** all of Columbus; **William J. Gallagher,** Worthington, all of Ohio

[73] Assignee: **Battelle Memorial Institute,** Columbus, Ohio

[21] Appl. No.: **319,756**

[22] Filed: **Dec. 29, 1972**

[51] **Int. Cl.²** **G21G 4/00**

[52] **U.S. Cl.** **250/493**

[58] **Field of Search** ..... 250/92, 401 P, 493; 331/94.5 A, 94.5 GP; 176/1

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Primary Examiner—Nelson Moskowitz

Attorney, Agent, or Firm—Philip M. Dunson

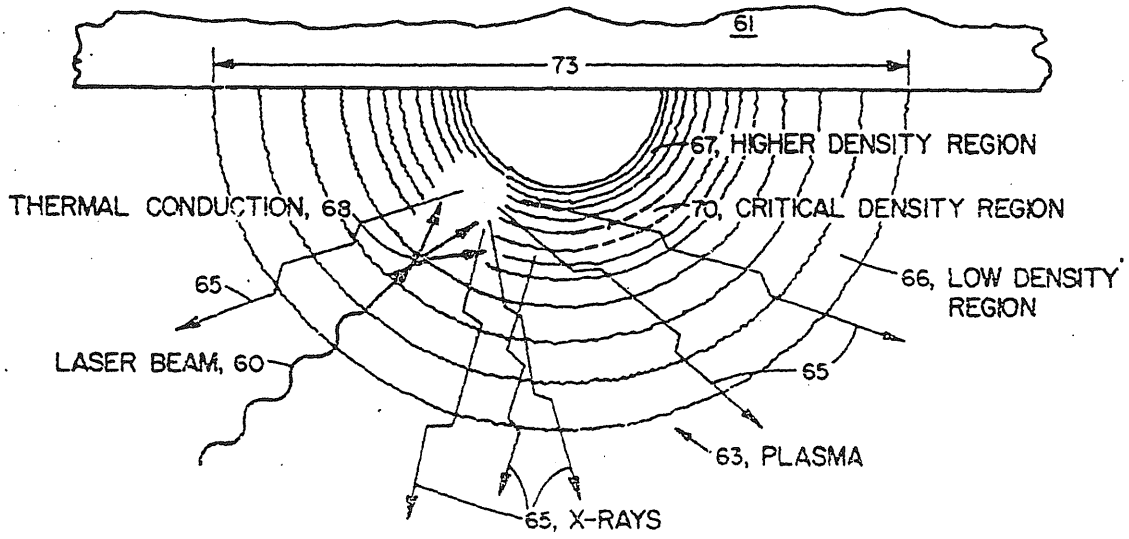
[57] **ABSTRACT**

A method of producing X-rays by directing radiant energy from a laser onto a target. Conversion efficiency of at least about 3 percent is obtained by providing the radiant energy in a low-power precursor pulse of approximately uniform effective intensity focused onto the surface of the target for about 1 to 30 nanoseconds so as to generate an expanding unconfined coronal plasma having less than normal solid density throughout and comprising a low-density (underdense) region wherein the plasma frequency is less than the laser radiation frequency and a higher-density (overdense) region wherein the plasma frequency is greater than the laser radiation frequency and, about 1 to 30 nanoseconds after the precursor pulse strikes the target, a higher-power main pulse focused onto the plasma for about 10^{-3} to 30 nanoseconds and having such power density and total energy that the radiant energy is absorbed in the underdense region and conducted into the overdense region to heat it and thus to produce X-rays therefrom with the plasma remaining substantially below normal solid density and thus facilitating the substantial emission of X-rays in the form of spectral lines arising from nonequilibrium ionization states.

The X-rays may be produced essentially as from a point source (i.e., they are spatially coherent) and thus are suitable for many applications that would otherwise require an X-ray laser. In some embodiments phase coherence is achieved, thus providing a true X-ray laser.

In a similar method, providing a controlled nuclear fusion reaction, the target comprises alternate layers of high-Z and lower-Z material.

20 Claims, 33 Drawing Figures



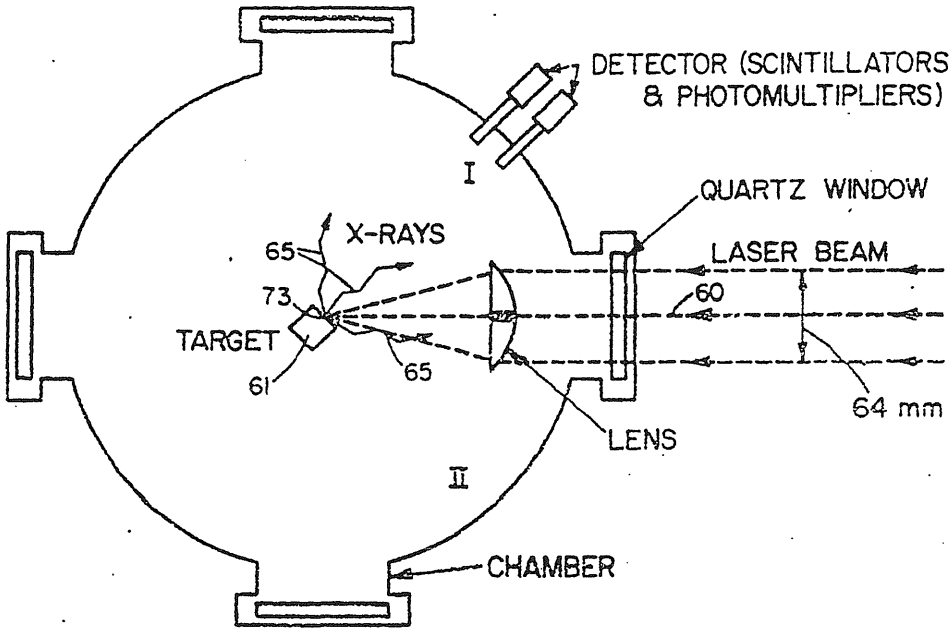


FIG. 1. BASIC EXPERIMENTAL CONFIGURATION USED FOR X-RAY PRODUCTION

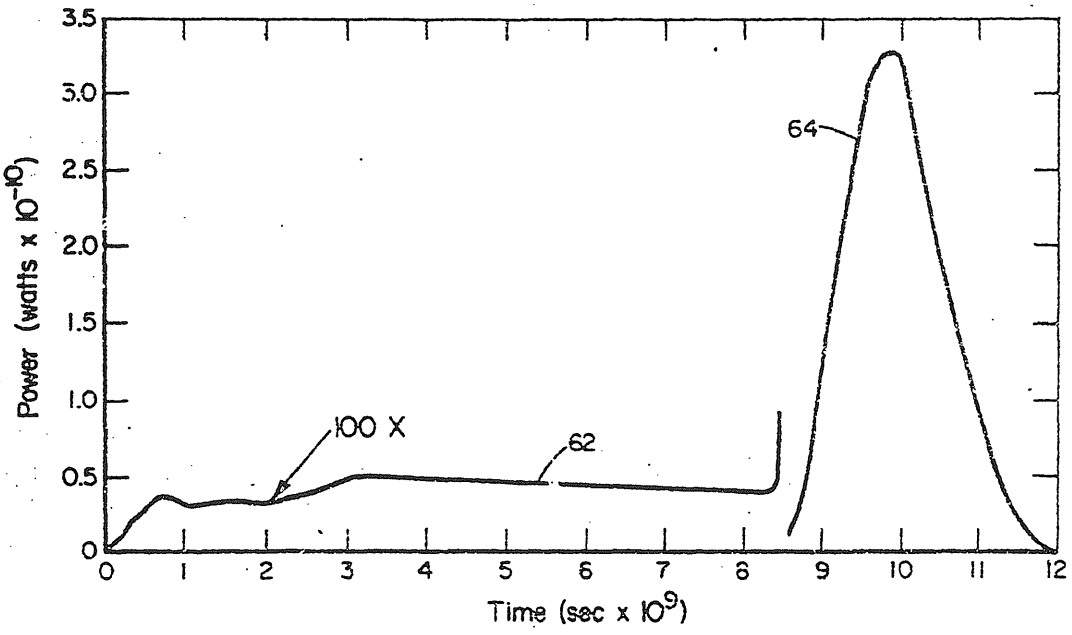


FIG. 2. LASER PULSE WITH FOOT

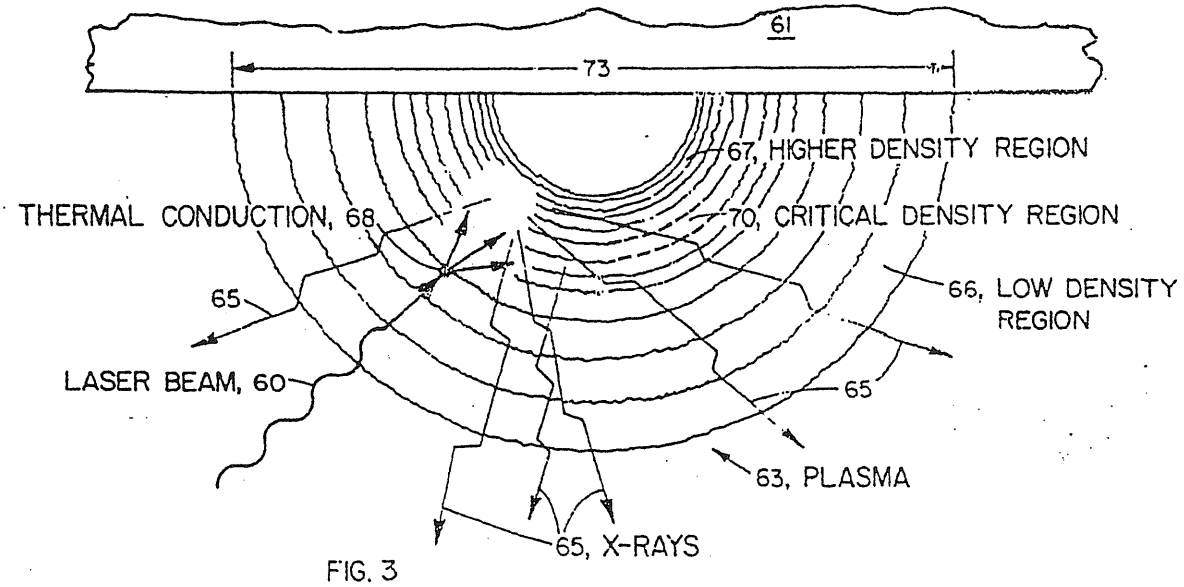


FIG. 3

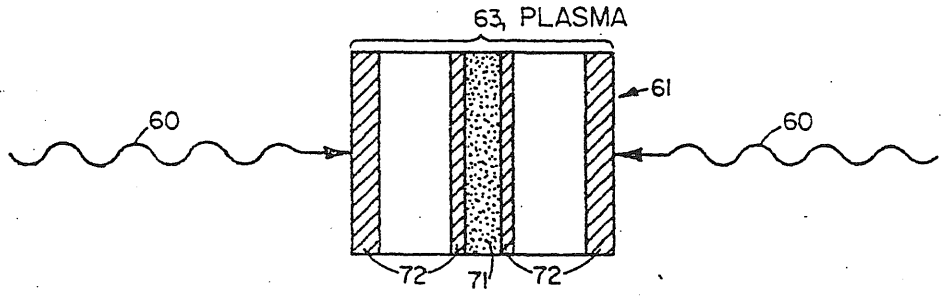


FIG. 4

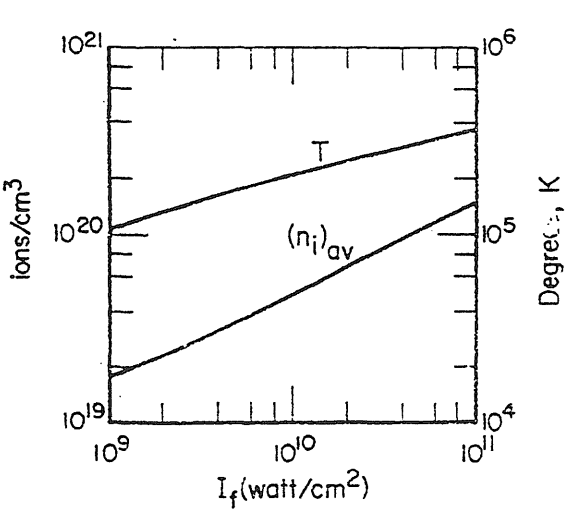


FIG. 5. TEMPERATURE AND AVERAGE ION DENSITY OF INITIAL IRON PLASMA AS PREDICTED BY EQUATIONS (A-27) AND (A-29)

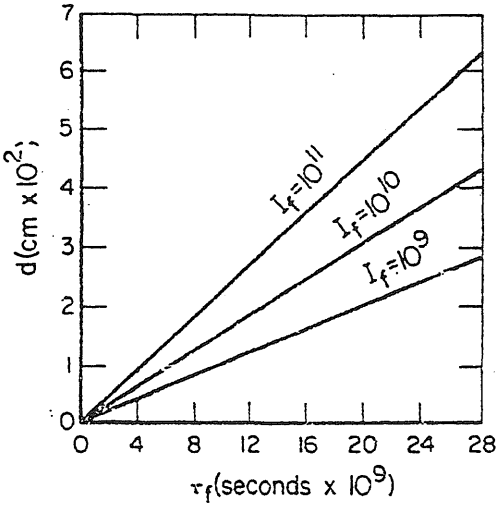


FIG. 6. THICKNESS OF INITIAL IRON PLASMA AS PREDICTED BY EQUATION (A-28)

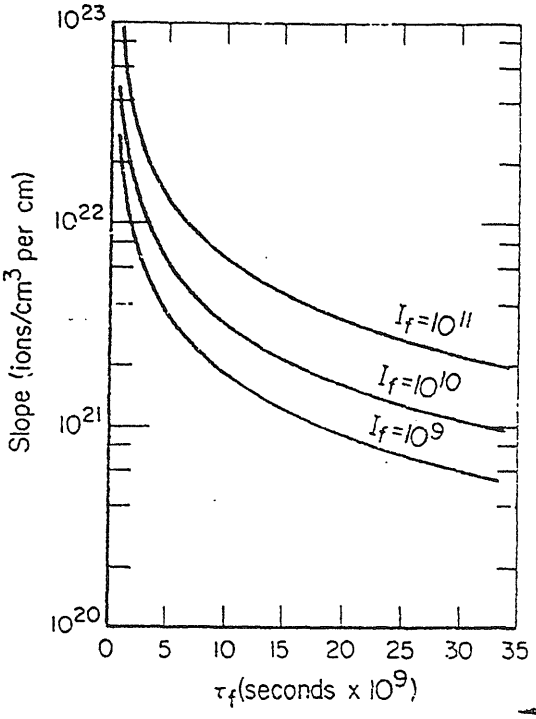


FIG. 7. SLOPE OF ION DENSITY PROFILE OF INITIAL IRON PLASMA CALCULATED BY PROCEDURE DESCRIBED IN THE TEXT

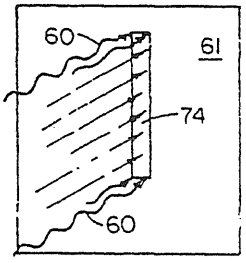


FIG. 8

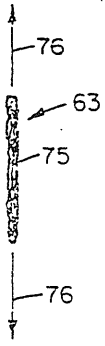


FIG. 9

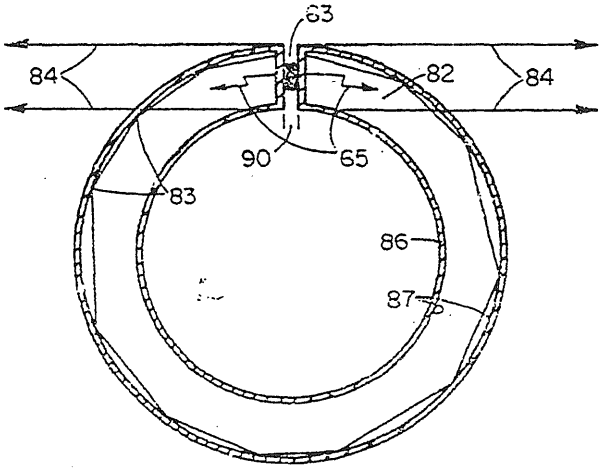


FIG. 11

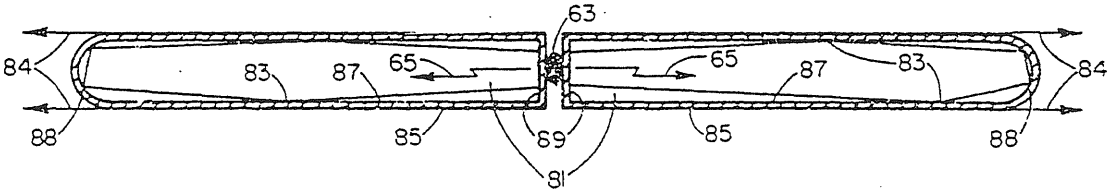


FIG. 10

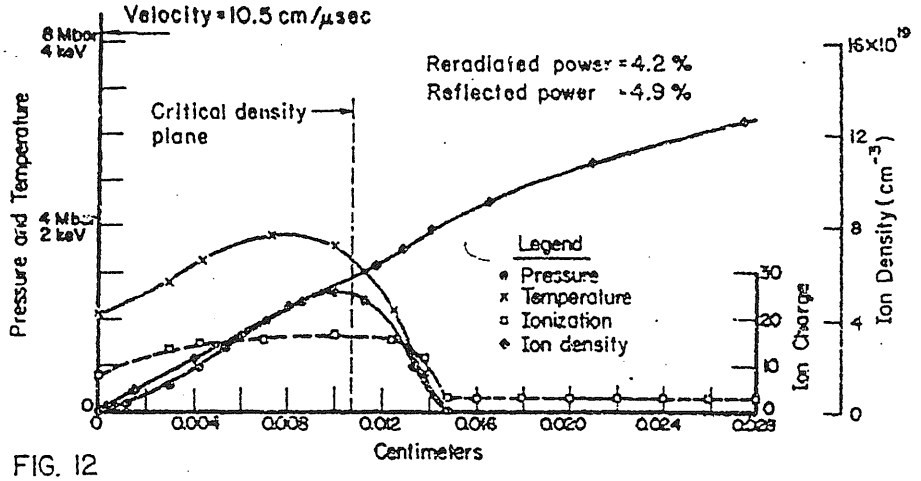


FIG. 12

Time = 33.4 Picoseconds

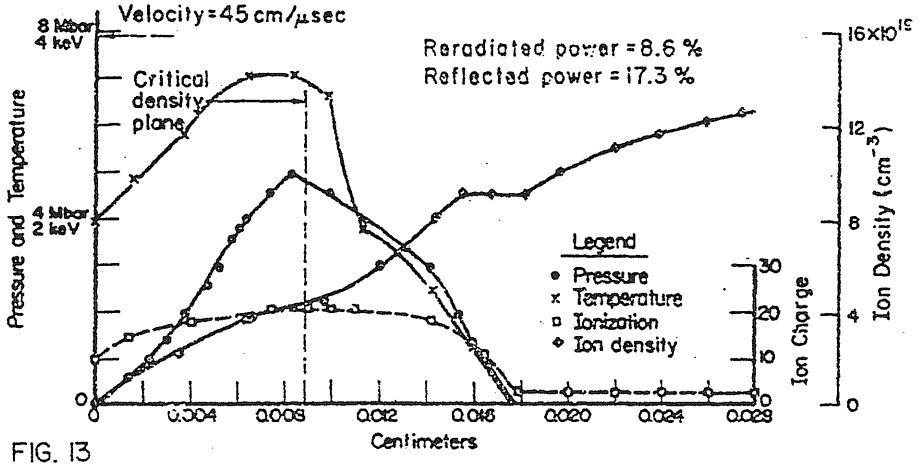


FIG. 13

Time = 86.8 Picoseconds

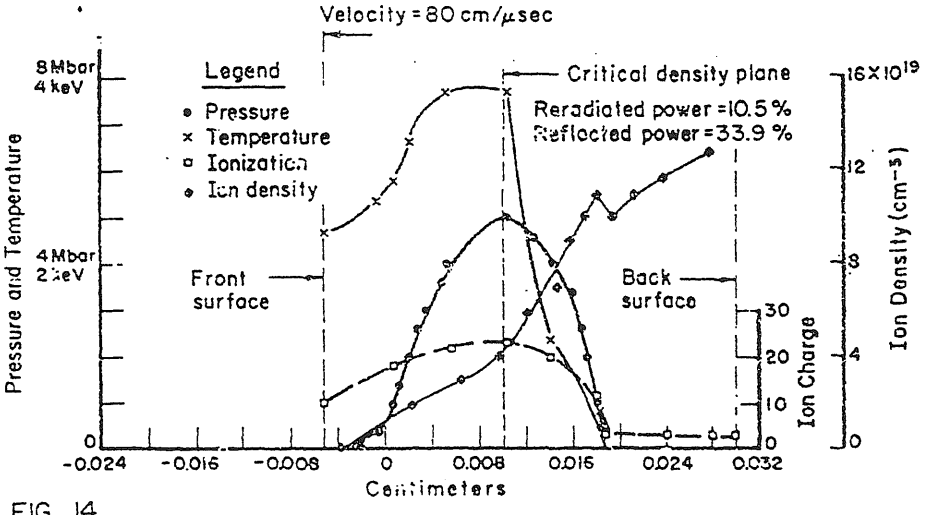


FIG. 14

Time = 135 Picoseconds

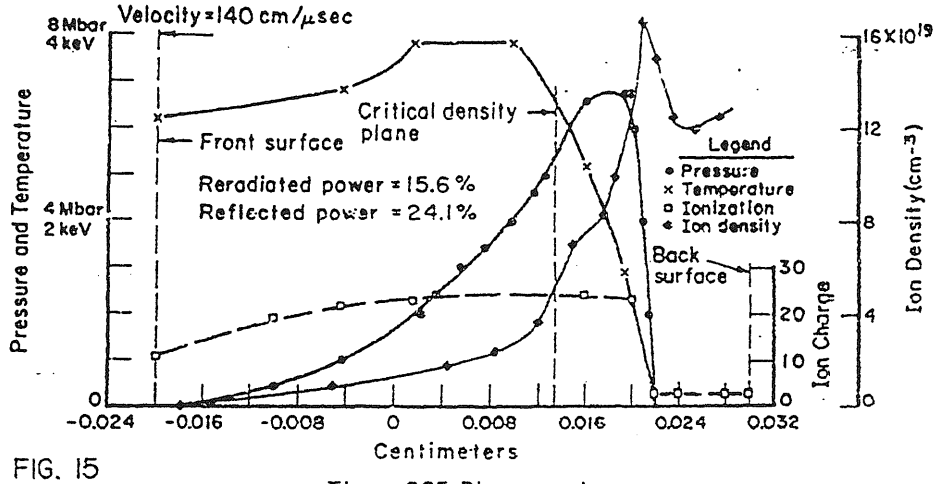


FIG. 15

Time = 265 Picoseconds

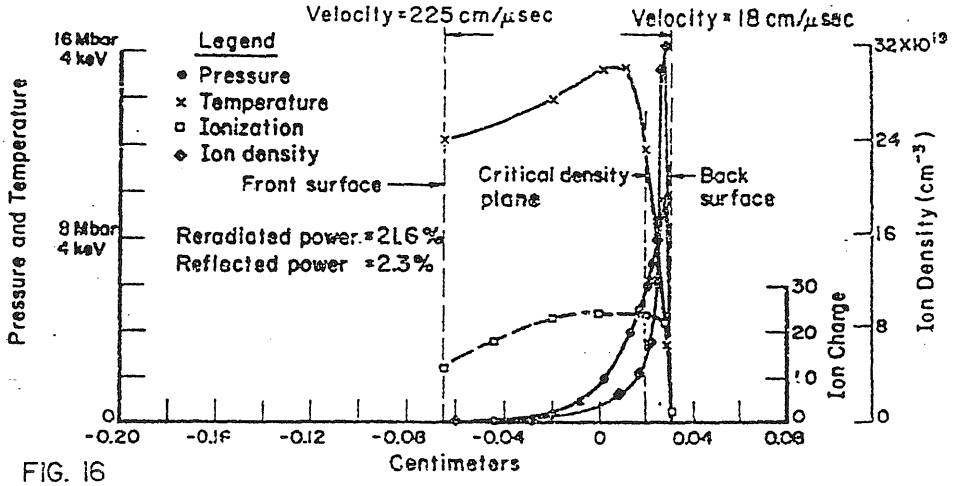


FIG. 16

Time = 500 Picoseconds

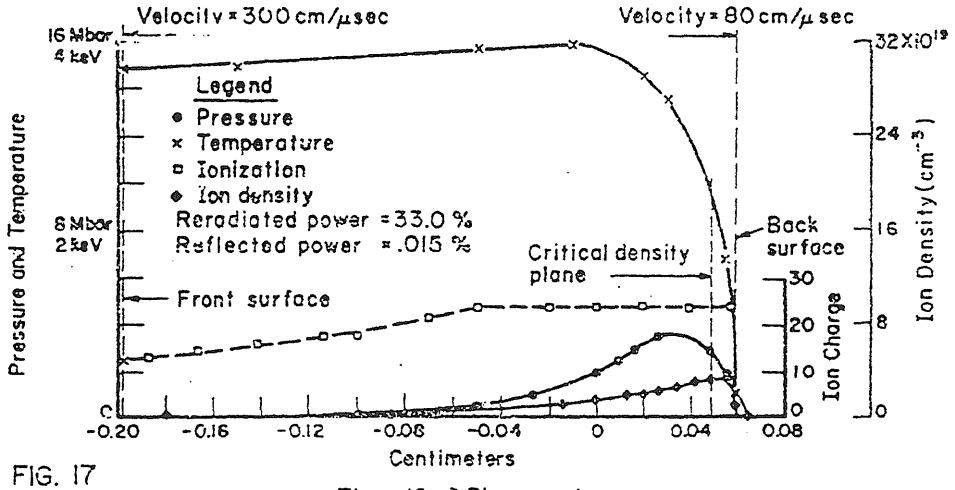


FIG. 17

Time = 1000 Picoseconds

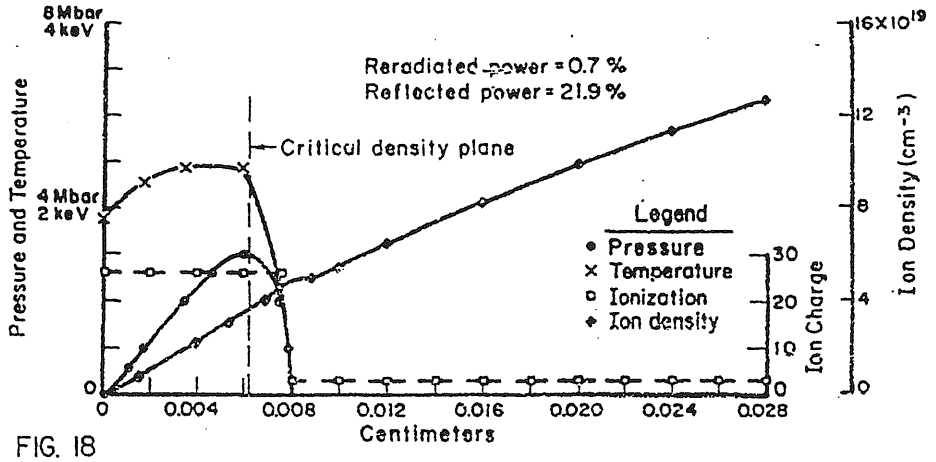


FIG. 18

Time = 33.4 Picoseconds

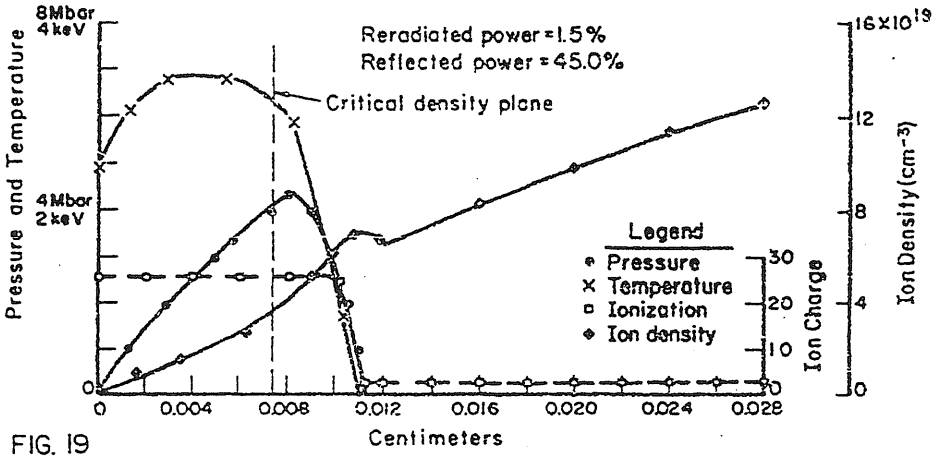


FIG. 19

Time = 83.9 Picoseconds

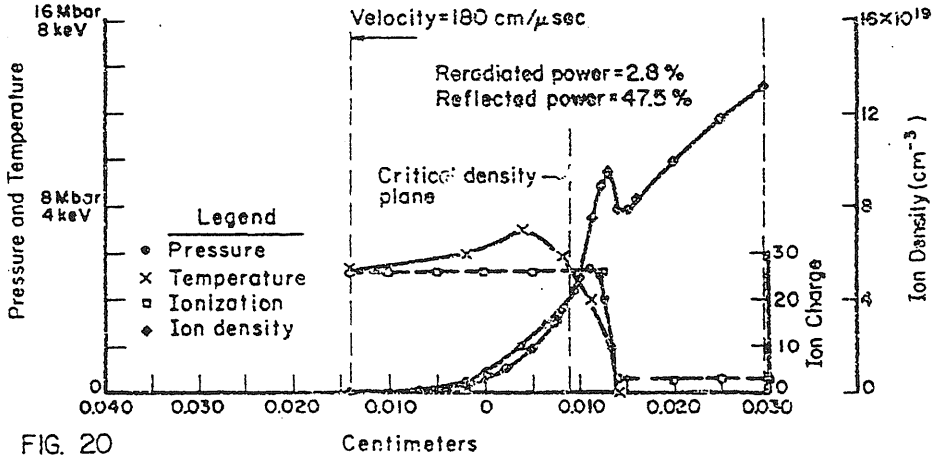


FIG. 20

Time = 143 Picoseconds

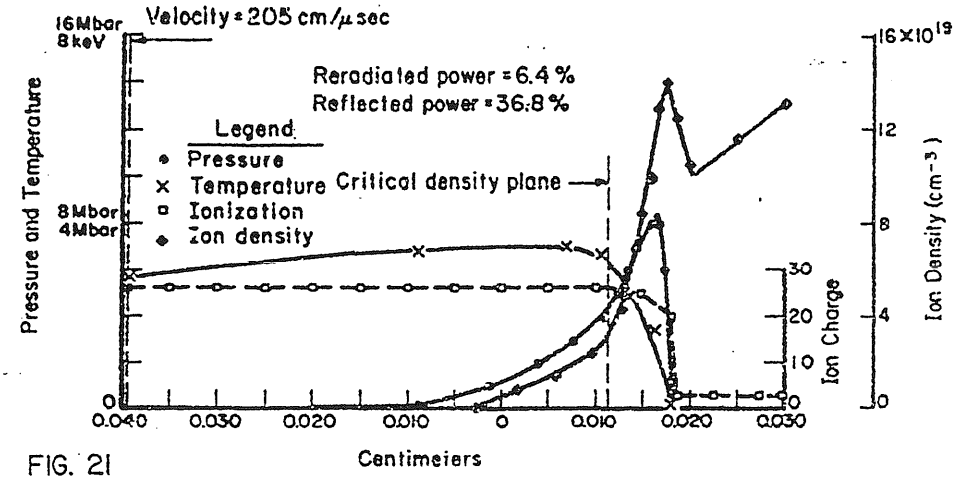


FIG. 21

Time = 256 Picoseconds

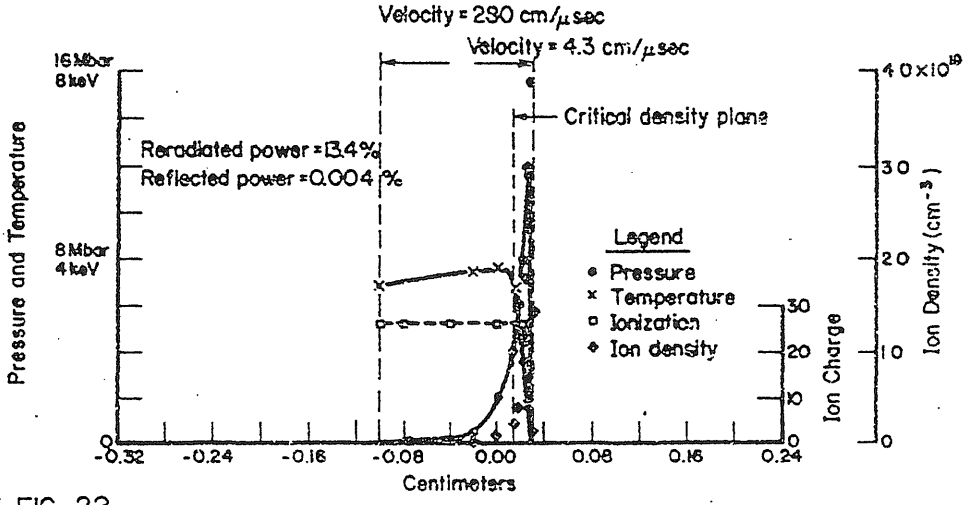


FIG. 22

Time = 502 Picoseconds

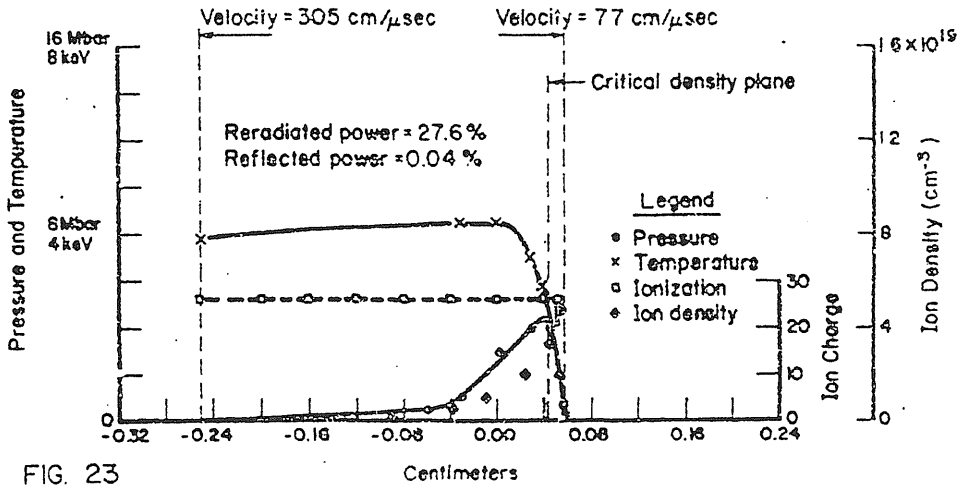


FIG. 23

Time = 1000 Picoseconds

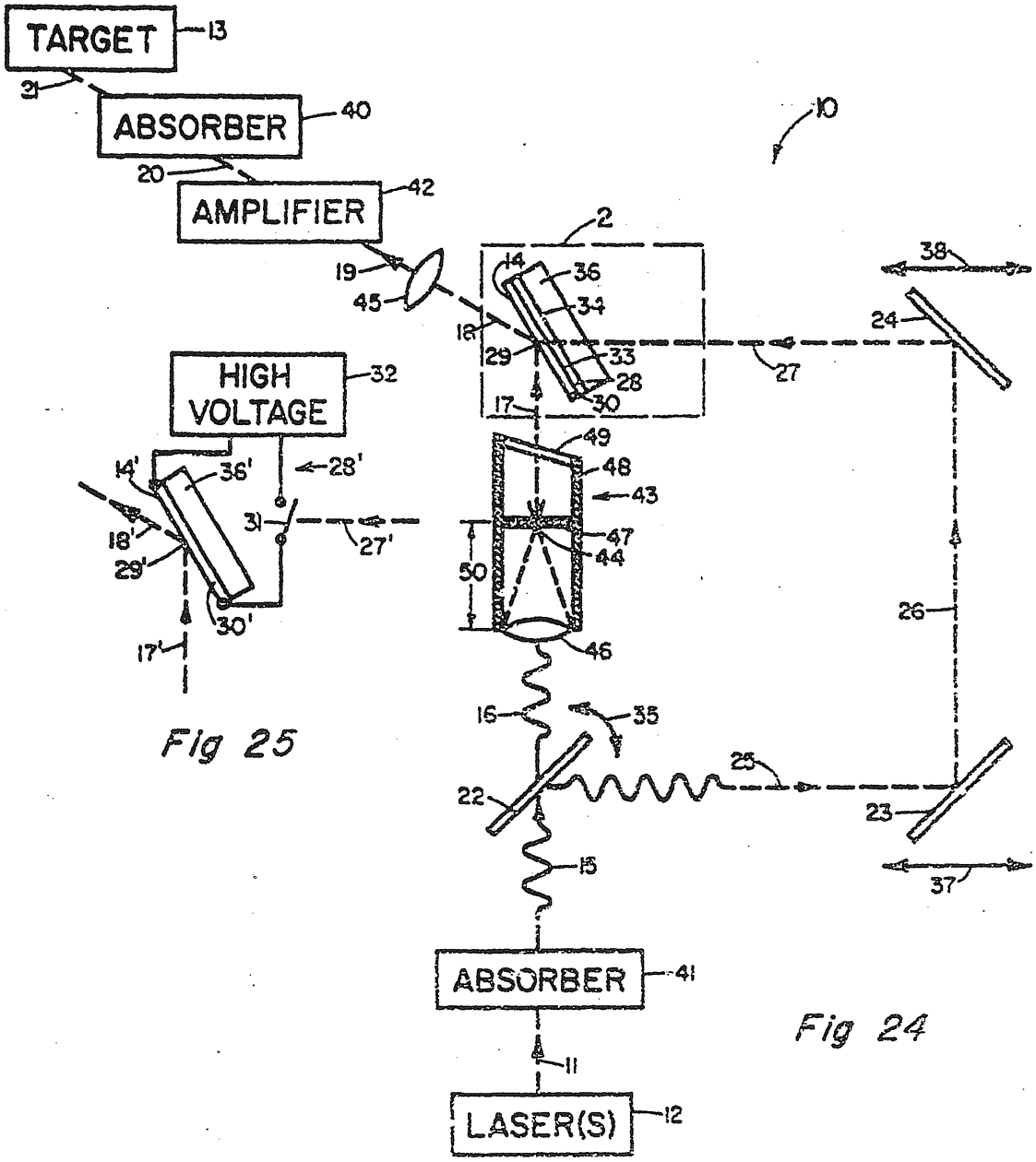

TARGET
13
21
ABSORBER
40
20
AMPLIFIER
42
10
2
19
45
14
36
34
38
24
18
29
33
28
30
27
HIGH VOLTAGE
32
17
49
48
43
14'
36'
28'
31
18'
29'
27'
47
44
50
26
30'
17'
46
16
35
25
22
23
15
37
ABSORBER
41
11
LASER(S)
12

Fig 25

Fig 24

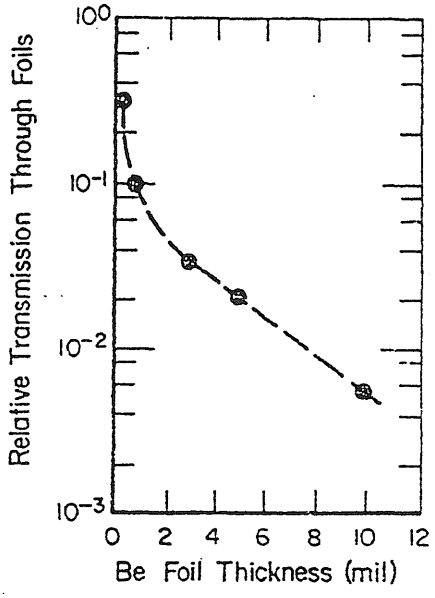


FIG. 26. X-RAY TRANSMISSION THROUGH BERYLLIUM FOILS

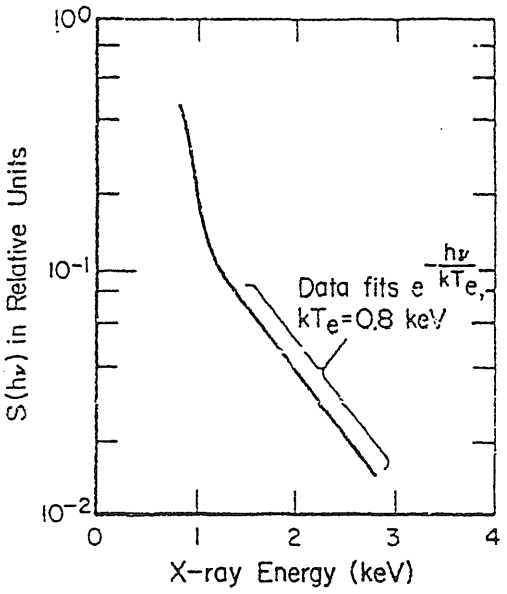


FIG. 27. X-RAY SPECTRAL DISTRIBUTION FROM IRON SLABS

Derived from X-ray transmission through Beryllium foil.

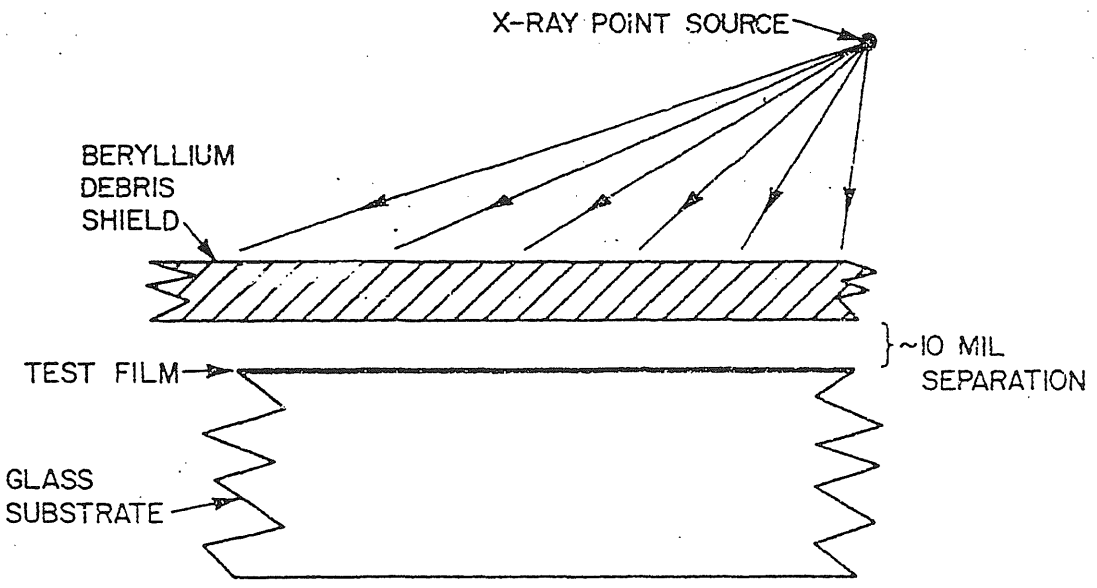


FIG. 28. MATERIAL DAMAGE THRESHOLD CALORIMETER

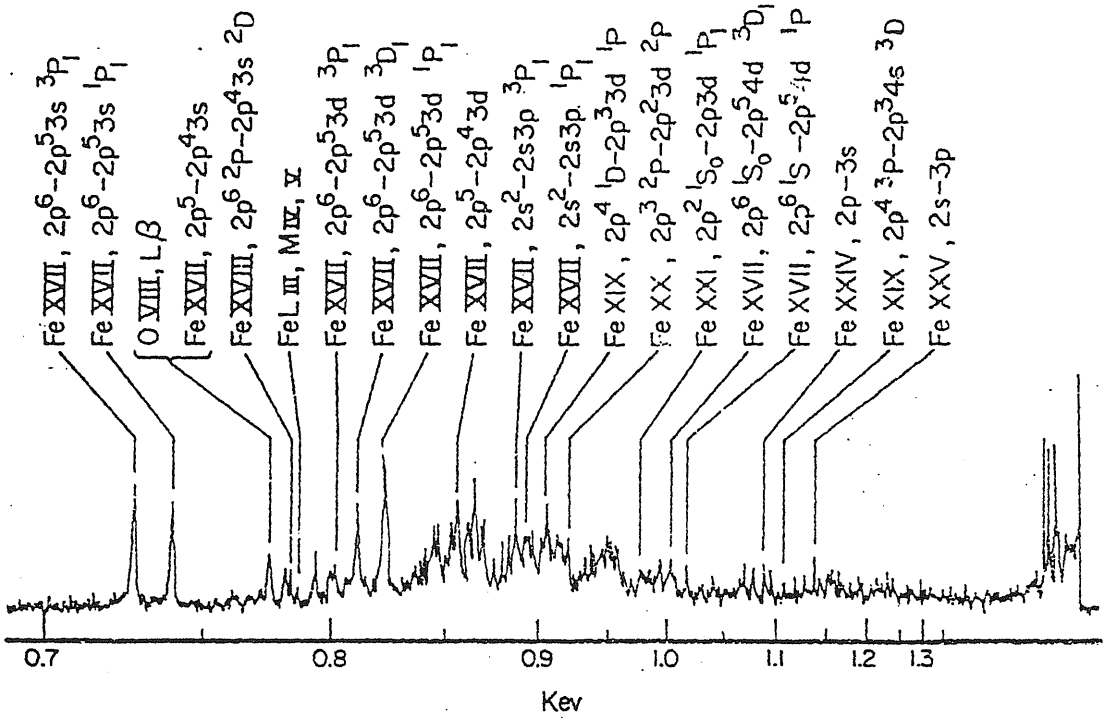


FIG. 29. SPECTROGRAPH OF X-RAYS FROM IRON SLAB TARGET USING BENT CRYSTAL SPECTROMETER

Laser flux is incident on iron slab at $\sim 10^{14}$ watts/cm^2.

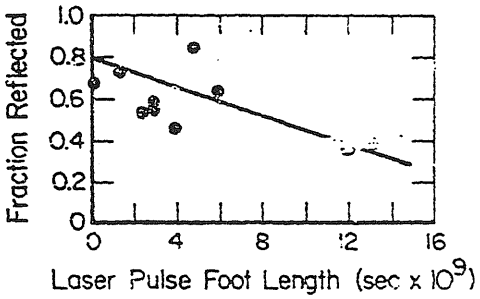


FIG. 30. LASER LIGHT REFLECTION VERSUS FOOT LENGTH

Laser flux is incident on iron slab at $\sim 10^{14}$ watts/cm^2.

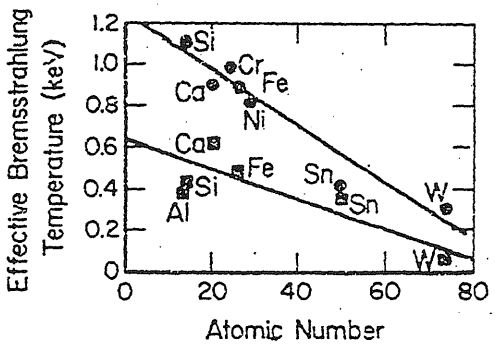


FIG. 31. EFFECTIVE BREMSSTRAHLUNG TEMPERATURE VERSUS ATOMIC NUMBER

Upper curve corresponds to $\sim 10^{14}$ watts/cm^2. Lower curve corresponds to $\sim 0.4 \times 10^{14}$ watts/cm^2.

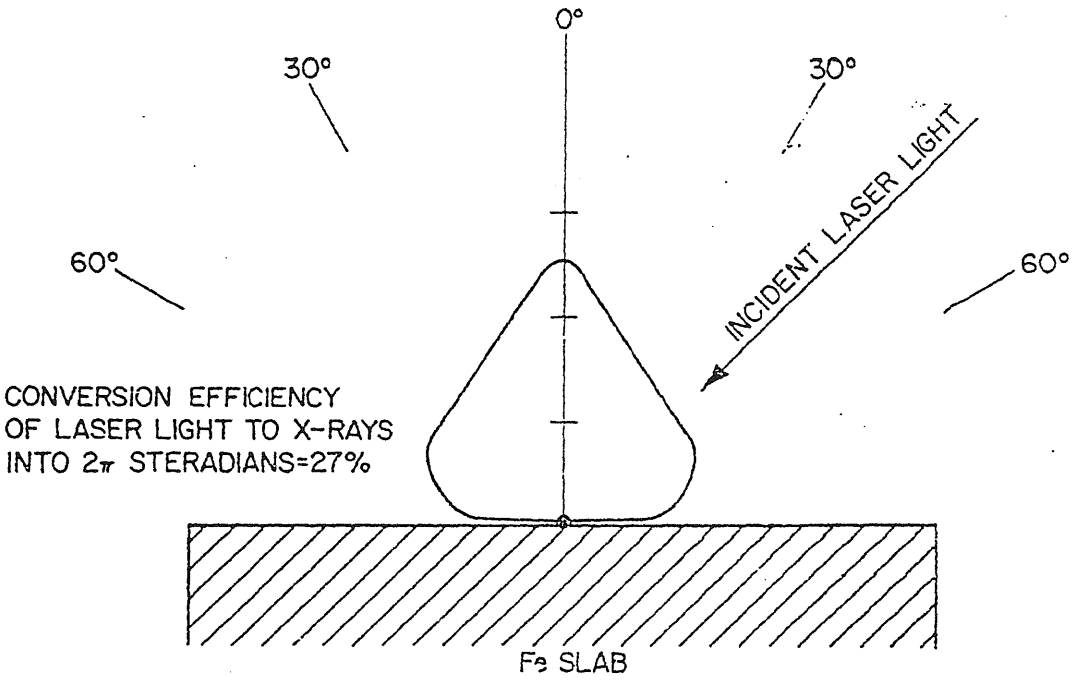


FIG. 32. X-RAY RADIATION PATTERN

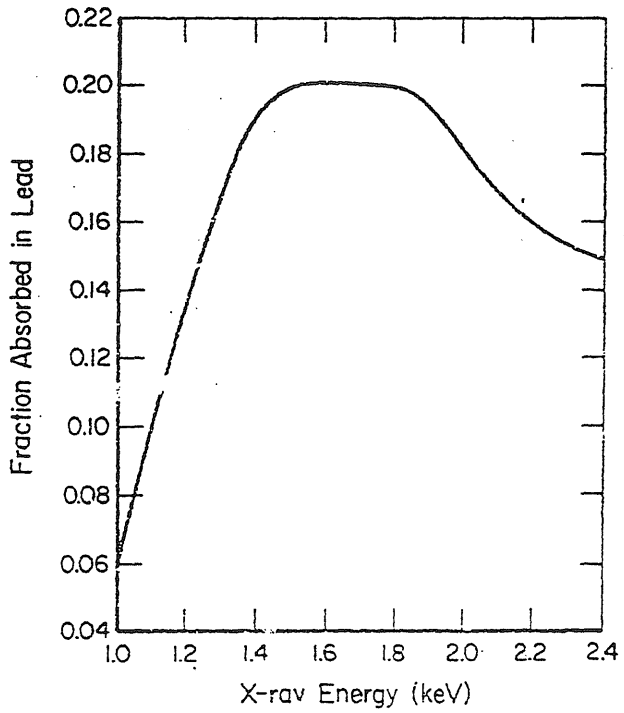


FIG. 33. FRACTION OF X-RAYS ABSORBED IN 2000 Å LEAD FILM AFTER PASSING THROUGH I MIL BERYLLIUM FOIL VERSUS ENERGY

PRODUCING X-RAYS

BACKGROUND

By bombarding a thick iron target with a high-power laser, a broad-band source of X-rays has been produced. The conversion efficiency of 1.06-micron laser light into X-rays is at least 10%, probably 15–20% and possibly 30–40%.

Above 1 kV the output was mainly spectral lines, and the major portion below 1 kV was probably lines, too. At energies above 1 kV, the conversion efficiency is about 5%.

The result can be a big step forward toward a brute-force X-ray laser. One possibility is to use a broad-band X-ray source of very high intensity as a laser pump.

A Hadron CGE-640 neodymium-doped glass laser is pulsed at 100 joules in 1 nanosec. The beam passes through an *f*/1 or *f*/3 lens, strikes a target at 45° with respect to the incident beam, and a plasma is produced in the target at the laser focus. The target is a 1-cm-thick slab, essentially infinitely thick to the laser. Targets of chromium, calcium, nickel, aluminum, lead, tungsten, and gold provide X-ray conversion with varying efficiencies. With chromium essentially the same efficiency is obtained as with iron.

The distribution of internal states in the atom, rather than the gross properties of the target, are what determines the output. That is, the spectrum and conversion efficiency depend on the atomic number Z of the target, and one can expect large conversion efficiencies from any material with Z above 10, provided one properly adjusts the precursor pulse or foot, a low-power pulse that precedes the main pulse. The purpose of the foot is to produce plasma so that the main pulse will strike a plasma rather than a solid.

For iron, the material used for most of the studies, with no foot one gets very soft X-rays. With a long foot one gets a few harder X-rays. With full parametric variation of foot size one gets an optimal value at 8–10 nanosec pulse duration.

Using a computer analysis to solve the rate equations resulting from a microscopic description of all the principal collisional and radiative processes in the experiment, good agreement is found between the calculation and experiment.

Experiments were made also with pellets, but most of the emphasis has been on slabs because they appear to be more useful in gaining basic data, although they may not be the best geometry. Similarly, emphasis has been on iron, although it may not be the best material.

Laser bombardment of high-Z materials appears promising for an X-ray laser, and also has other used. In fact emphasis has primarily been on other uses.

Because of the good conversion efficiency and considerable line output, it appears that by making a different selection of targets, most of the energy could be made to come out in a few lines. When one pulses a material rapidly compared to the lifetime of the states involved, one would expect to produce metastable states. If superradiant levels are present in the laser focus, the device would be close to a laser. The only problem left would be to make a cavity.

The interaction of a laser beam with high-Z materials is also useful for controlled fusion. The technique may play a key role in lowering the threshold laser energies for achieving fusion. Although most of the emphasis in this effort has been with light materials, high-Z materials could be used in conjunction with deuterium and tritium, perhaps in different layers.

An intense point source of X-rays with a high conversion efficiency of laser light into X-rays has been developed. The X-rays emanate from a spot of approximately 100 microns diameter, and a large fraction of the X-rays (sometimes 50% or more) are emitted in the form of spectral lines.

An important implication of these properties is the fact that many of the applications that are generally cited in justification of an X-ray laser can be accomplished with a point source (i.e., "spatially coherent" source) of X-ray lines, or even with a point source of broad band X-rays. For example, a significant fraction of the X-rays can be focused to another point or into a parallel beam by means of critical angle reflectors, Fresnel zone plates, or Bragg diffractors.

It is calculated that the X-ray emission in a single spectral line can exceed 1% of the indicent laser light. This can also be true when a substantial amount of amplification through stimulated emission occurs. In the latter case the device constitutes an actual X-ray laser, which can provide a narrow beam if the plasma shape is a suitably long cylinder or an X-ray cavity is constructed. Indeed, in addition to the fact that it can serve many of the functions of an X-ray laser, the point source device is only one step away from a true X-ray laser. Large outputs of X-ray lines are being produced in a highly nonequilibrium plasma, and theory says that a substantial amount of stimulated emission can occur with some adjustments of plasma temperature of target configuration.

Statements are often made that picosecond or terrawatt pumping pulses are required for an X-ray laser. This appears to be untrue. Calculations indicate that a nanosecond laser pulse with 100 to 1000 joules of energy should be more than adequate.

Another route to an X-ray laser is to use the X-rays generated by the present technique to knock out inner shell electrons from atoms in a separate laser medium and thereby create a population inversion.

SUMMARY OF THE INVENTION

A typical method of producing X-rays according to the present invention comprises directing radiant energy from a laser onto a target, and conversion efficiency of at least bout 3 percent is obtained by providing the radiant energy in a low-power precursor pulse of approximately uniform effective intensity focused onto the surface of the target for about 1 to 30 nanoseconds so as to generate an expanding unconfined coronal plasma having less than normal solid density throughout and comprising a low-density (underdense) region wherein the plasma frequency is less than the laser radiation frequency and a higher-density (overdense) region wherein the plasma frequency is greater than the laser radiation frequency and, about 1 to 30 nanoseconds after the precursor pulse strikes the target, a higher-power main pulse focused onto the plasma for about 10^{-3} to 30 nanoseconds and having such power density and total energy that the radiant energy is absorbed in the underdense region and conducted into the overdense region to heat it and thus to produce X-rays therefrom with the plasma remaining substantially below normal solid density and thus facilitating the substantial emission of X-rays in the form of spectral lines arising from nonequilibrium ionization states.

The target typically consists essentially of an element having a high atomic number Z, i.e., an atomic number Z greater than 10. Typically the target consists essentially of iron, calcium, chromium, nickel, aluminum, lead, tungsten, or gold.

The amplitude, duration, and shape of the precursor pulse typically are adjusted to control the intensity and spectral content of the X-rays. The precursor pulse typically comprises about 0.01 to 5 joules (about 10^{10} to 10^{12} watts per square centimeter), and strikes the target at an angle of about 20° to 70° from its surface.

The main pulse typically comprises at least about 0.1 joule, preferably about 10 to 200 joules in about 1 to 3 nanoseconds.

In a typical embodiment, the target consists essentially of iron and the duration of the precursor pulse is about 8 to 10 nanoseconds.

The electron density in the low-density region of the plasma typically is about 10^{16} to 10^{21} per cubic centimeter, and in the higher-density region about 10^{19} to 10^{25} per cubic centimeter. The radiant energy typically is focused onto a spot on the target having a diameter of about 10 to 1000 microns. The volume of the plasma typically is about 10^{-6} to 10^{-3} cubic centimeter, the thickness of the plasma in any direction being about 0.001 to 0.1 centimeter.

For low energy applications the X-rays are emitted predominantly in the form of spectral line.

The radiant energy may be focused onto a spot on the target having a diameter of about 10 to 100 microns, generating a plasma of about the same diameter, to form substantially a point source of X-rays and thus to provide substantially the advantages of stimulated emission of X-rays.

In some embodiments of the invention the composition of the target and the temperature of the plasma are selected to provide a substantial amount of stimulated emission of X-rays.

In other embodiments X-rays are directed to impinge upon a fluorescent target so as to remove inner shell electrons from atoms thereof and thereby create a population inversion.

In a typical method of providing stimulated emission of X-rays by directing radiant energy onto a target to create by means of a pumping mechanism some upper and lower laser levels, the required population inversion is not established by the pumping mechanism alone, but by the combined action of the pumping mechanism and a quenching mechanism that extinguishes the lower laser level at a rate sufficient to establish and continuously maintain the inversion. The pumping mechanism typically comprises excitation by collisions of electrons and ions or by dielectronic recombination. The quenching mechanism typically comprises Auger transitions, Coster-Kronig transitions, or collisions. The radiant energy may be from a laser, or it may comprise a beam of electrons. The pumping mechanism may comprise a beam of electrons.

In some embodiments the pumping mechanism is sufficient to create a population inversion but not to maintain it. In others the pumping mechanism is sufficient to produce X-rays but not to create a population inversion.

Where convenient, the radiant energy may be furnished as a pulse having a duration that is less than the lifetime of the upper transition state involved to produce stimulated emission of X-rays from the highly populated levels therein. The upper laser level is metastable in some cases.

For stimulated emission of X-rays, where the radiant energy comprises a pumping pulse having a duration that is longer than the lifetime of the upper state involved, overpopulation of the lower laser level may be avoided by depopulating it faster than it is populated by transitions from the upper laser level and other atomic levels, to maintain continuous wave operation during a substantial portion of the pumping pulse. Typically the lower laser level is depopulated by Auger transitions, Coster-Kronig transitions, or collisions; and the upper laser level is excited by electron-ion collisions, dielectronic recombination, three-body recombination, or photoionization. Typically a beam of X-rays is directed onto a target to remove electrons from an inner shell or subshell by photoionization, then electrons decay from an exterior shell or subshell filling the holes in the inner shell or subshell and leaving holes in the exterior shell or subshell, the holes in the exterior shell or subshell are then filled by Auger or Coster-Kronig transitions from more exterior shells or subshells, thereby eliminating the lower laser states and decreasing the population in the lower laser level. In some embodiments a beam of X-rays is directed onto a target comprising essentially a material having an atomic number Z less than about 40 to remove K-shell electrons by photoionization, then electrons decay from the L shell filling the holes in the K shell and leaving holes in the L shell, the holes in the L shell are then filled by Auger transitions from the M and N shells or Coster-Kronig transitions from other subshells of the L shell, thereby eliminating the lower laser states and decreasing the population in the lower laser level.

Laser action can be obtained where the radiant energy is focused onto a substantially rectangular spot on the target having a length at least about 10 times its width to generate a plasma substantially in the shape of an elongate cylinder that forms a source of spontaneously emitted X-rays and amplifies then by the process of stimulated emission therein predominantly in the directions of its axis. The spot typically is about 1 to 100 microns wide and about 100 to 10^5 microns long, and the cylindrical plasma that is generated is about 1 to 1000 microns in diameter and about 100 to 10^5 microns long.

Laser action can be provided where an amplifying cavity is positioned adjacent the plasma to receive a substantial proportion of the X-rays produced and by multiple reflections to direct the X-rays repeatedly through the cavity and the plasma to amplify them and to direct them the coherent amplified waves predominantly in a predetermined path. A typical amplifying cavity comprises a hollow guide that is substantially circular in cross section and due to reflection at or below the critical angle has a substantially completely reflective side surface. In a typical embodiment the guide comprises a pair of coaxial substantially circular cylinders of which one end of each is substantially completely reflective (as by having an appropriately arranged reflector configuration which employs critical angle or Bragg diffraction processes) and the other end is positioned adjacent to the plasma. In another the guide comprises substantially a torus having a gap therein in the shape of a thin disk substantially coaxial therewith, and the plasma is positioned in the gap.

In a method of providing a controlled nuclear fusion reaction by directing radiant energy from a laser onto a target to create a plasma, the present invention includes

the improvement that comprises including in the composition of the target an element having a high atomic number Z, together with the usual deuterium, tritium, or other lower-Z material. Typically the target comprises at least one layer of high-Z material and at least one layer of lower-Z material. In a typical embodiment the high-Z material comprises essentially iron and the lower-Z material comprises essentially lithium deuteride.

BRIEF DESCRIPTION OF THE DRAWINGS

The drawings all represent features or other aspects of the present invention.

FIG. 1 is a schematic elevational view of typical apparatus for practicing the invention.

FIG. 2 is graph of a typical laser pulse with foot (precursor pulse).

FIG. 3 is a schematic sectional representation of a typical plasma and associated phenomena.

FIG. 4 is a schematic sectional view of a typical target.

FIGS. 5, 6, and 7 are graphs of typical plasma properties.

FIG. 8 is a schematic view representing radiant energy focused onto a substantially rectangular spot on a target.

FIG. 9 is a schematic view representing a substantially cylindrical plasma generated as in FIG. 8.

FIGS. 10 and 11 are schematic sectional views of typical amplifying cavities.

FIGS. 12–17 are graphs of typical properties in a nonequilibrium ionization.

FIGS. 18–23 are similar graphs for an equilibrium ionization.

FIG. 24 is a schematic view illustrating apparatus for avoiding damage to high-power lasers used in the invention.

FIG. 25 is a schematic view of an alternative form of the portion of the apparatus in the rectangle 2 in FIG. 24.

FIG. 26 is a graph of X-ray transmission through beryllium foils.

FIG. 27 is a graph of X-ray spectral distribution from iron slabs.

FIG. 28 is a schematic sectional view of a calorimeter for measuring material damage threshold,

FIG. 29 is a densitometer trace of a film recording the spectrograph of X-rays from an iron slab target.

FIG. 30 is a graph of laser light reflection versus foot length for an iron slab target.

FIG. 31 is a graph of effective bremsstrahlung temperature versus atomic number.

FIG. 32 is a schematic sectional representation of a typical X-ray radiation pattern.

FIG. 33 is a graph of X-ray absorption.

The drawings of apparatus are highly magnified and simplified schematic representations and of course are not to scale.

DESCRIPTION OF PREFERRED EMBODIMENTS

Referring first to FIG. 1, a typical method of producing X-rays according to the present invention comprises directing radiant energy 60 from a lase onto a target 61, and high conversion efficiency is obtained by at least one of the following steps:

a. providing the radiant energy 60 in a low-power precursor pulse 62 (see FIG. 2) focused onto the target 61 to generate a plasma 63 (FIG. 3) and shortly thereafter a higher-power main pulse 64 (FIG. 2) focused onto the plasma 63 to heat it and thus to produce X-rays 65 therefrom;

b. focusing the radiant energy 60 onto a target 61 (FIG. 4) shaped to contain or compress the plasma 63 generated by the energy 60 so as to increase the density of the plasma 63, to increase its duration in a dense state, or both;

c. providing the radiant energy 60 in sufficient power to generate a plasma 63 having a low-density region 66 wherein the plasma frequency is less than the laser radiation frequency and a higher-density (overdense) region 67 wherein the plasma frequency is greater than the laser radiation frequency so that the radiant energy is absorbed in the low-density region (as at 68) and thermally conducted as indicated at 69 through a critical density region 70 into the higher-density region 67 where the bulk of the X-rays 65 are produced;

d. focusing the radiant energy onto a target 61 (FIG. 4) containing fusionable material 71 and material 72 capable of producing a substantial quantity of X-rays 65 so as to provide a controlled thermonuclear reaction therein and thus increase the total energy available to produce X-rays.

Typically a conversion efficiency of at least about 3 percent is obtained by providing the radiant energy in a low-power precursor pulse 62 of approximately uniform effective intensity (as in FIG. 2) focused onto the surface of the target 61 for about 1 to 30 nanoseconds so as to generate an expanding unconfined coronal plasma 63 (FIG. 3) having less than normal solid density throughout and comprising a low-density (underdense) region 66 wherein the plasma frequency is less than the laser radiation frequency and a higher-density (overdense) region 67 wherein the plasma frequency is greater than the laser radiation frequency and, about 1 to 30 nanoseconds after the precursor pulse strikes the target, a higher-power main pulse focused onto the plasma for about 10^{-3} to 30 nanoseconds and having such power density and total energy that the radiant energy is absorbed in the underdense region and thermally conducted as indicated at 68 into the overdense region to heat it and thus to produce X-rays 65 therefrom with the plasma 63 remaining substantially below normal solid density and thus facilitating the substantial emission of X-rays in the form of spectral lines (as in FIG. 29) arising from nonequilibrium ionization states.

The main pulse 64 typically comprises at least about 0.1 joule in about 10^{-3} to 30 nanoseconds, preferably about 10 to 200 joules in about 1 to 3 nanoseconds, and strikes the plasma 63 about 1 to 30 nanoseconds after the precursor pulse strikes the target.

In a typical embodiment, the target 61 consists essentially of iron and the duration of the precursor pulse 62 is about 8 to 10 nanoseconds, as in FIG. 2.

The electron density in the low-density region 66 of the plasma 63 typically is about 10^{16} to 10^{21} per cubic centimeter, and in the higher-density region 67 about 10^{19} to 10^{25} per cubic centimeter. The radiant energy 60 typically is focused onto a spot 73 on the target 62 having a diameter of about 10 to 1000 microns. The volume of the plasma 63 typically is about 10^{-6} to 10^{-3} cubic centimeter, the thickness of the plasma 63 in any direction being about 0.001 to 0.1 centimeter.

For low energy applications the X-rays 65 are emitted predominantly in the form of spectral lines, as in FIG. 29.

The radiant energy 60 may be focused onto a spot 73 on the target 61 having a diameter of about 10 to 100 microns, generating a plasma 63 of about the same diameter, to form substantially a point source of X-rays 65 and thus to provide substantially the advantages of stimulated emission of X-rays.

In some embodiments of the invention the composition of the target 62 and the temperature of the plasma 63 are selected to provide a substantial amount of stimulated emission of X-rays 65.

In other embodiments X-rays 65 are directed to impinge upon a fluorescent target so as to remove inner shell electrons from atoms thereof and thereby create a population inversion.

In a typical method of providing stimulated emission of X-rays by directing radiant energy onto a target to create by means of a pumping mechanism some upper and lower laser levels, the required population inversion is not established by the pumping mechanism alone, but by the combined action of the pumping mechanism and a quenching mechanism that extinguishes the lower laser level at a rate sufficient to establish and continuously maintain the inversion. The pumping mechanism typically comprises excitation by collisions of electrons and ions or by dielectronic recombination. The quenching mechanism typically comprises Auger transitions, Coster-Krönig transitions, or collisions. The radiant energy may be from a laser, or it may comprise a beam of electrons. The pumping mechanism may comprise a beam of electrons.

In some embodiments the pumping mechanism is sufficient to create a population inversion but not to maintain it. In others the pumping mechanism is sufficient to produce X-rays but not to create a population inversion.

Where convenient, the radiant energy may be furnished as a pulse having a duration that is less than the lifetime of the upper transition state involved to produce stimulated emission of X-rays from the highly populated levels therein. The upper laser level is metastable in some cases.

For stimulated emission of X-rays, where the radiant energy comprises a pumping pulse having a duration that is longer than the lifetime of the upper state involved, overpopulation of the lower laser level may be avoided by depopulating it faster than it is populated by transitions from the upper laser level and other atomic levels, to maintain continuous wave operation during a substantial portion of the pumping pulse. Typically the lower laser level is depopulated by Auger transitions, Coster-Krönig transitions, or collisions; and the upper laser level is excited by electron-ion collisions, dielectronic recombination, three-body recombination, or photoionization. Typically a beam of X-rays is directed onto a target to remove electrons from an inner shell or subshell by photoionization, then electrons decay from an exterior shell or subshell filling the holes in the inner shell or subshell and leaving holes in the exterior shell or subshell, the holes in the exterior shell or subshell are then filled by Auger or Coster-Krönig transitions from more exterior shells or subshells, thereby eliminating the lower laser states and decreasing the population in the lower laser level. In some embodiments a beam of X-rays is directed onto a target comprising essentially a material having an atomic number Z less than about 40 to remove K-shell electrons by photoionization, then electrons decay from the L shell filling the holes in the K shell and leaving holes in the L shell, the holes in the L shell are then filled by Auger transitions from the M and N shells or Coster-Krönig transitions from other subshells of the L shell, thereby eliminating the lower laser states and decreasing the population in the lower laser level.

Laser action can be obtained where the radiant energy 60 is focused onto a substantially rectangular spot 74 on the target 61, as in FIG. 8, having a length at least about ten times its width to generate a plasma 63 substantially in the shape of an elongate cylinder 75, as in FIG. 9, that forms a source of spontaneously emitted X-rays 76 and amplifies them by the process of stimulated emission therein predominantly in the directions of its axis. The spot 74 typically is about 1 to 100 microns wide and about 100 to 10^5 microns long, and the cylindrical plasma 75 that is generated is about 1 to 1000 microns in diameter and about 100 to 10^5 microns long.

Laser action can be provided where an amplifying cavity such as 81 (FIG. 10) or 82 (FIG. 11) is positioned adjacent the plasma 63 to receive a substantial proportion of the X-rays produced and by multiple reflections, provided by Bragg angle or critical angle reflections, or both, as at 83, to direct the X-rays 65 repeatedly through the cavity 81 or 82 and the plasma 63 to amplify them and to direct the coherent amplified waves predominantly in a predetermined path, as indicated at 84. A typical amplifying cavity 81 or 82 comprises a hollow guide 85 (FIG. 10) or 86 (FIG. 11) that typically is substantially circular in cross section and due to reflection at or below the critical angle has a substantially completely reflective side surface 87. In a typical embodiment (FIG. 10) the guide 85 comprises a pair of coaxial substantially circular cylinders 85 of which one end 88 of each is substantially completely reflective (as by having an appropriately arranged reflector configuration which employs critical angle or Bragg diffraction processes) and the other end 89 is positioned adjacent to the plasma 63. In another typical embodiment (FIG. 11) the guide 86 comprises substantially a torus having a gap therein (at 90) in the shape of a thin disk substantially coaxial therewith, and the plasma 63 is positioned in the gap 90.

In a method of providing a controlled nuclear fusion reaction by directing radiant energy 60 from a laser onto a target 61 as in FIG. 4 to create a plasma 63, the present invention includes the improvement that comprises including in the composition of the target 61 an element 72 having a high atomic number Z, together with the usual deuterium, tritium, or other lower-Z material at 71. Typically the target 61 comprises at least one layer 72 of high-Z material and at least one layer 71 of lower-Z material. In a typical embodiment the high-Z material 72 comprises essentially iron and the lower-Z material 71 comprises essentially lithium deuteride. Other useful targets are described in Reference 10.

EXAMPLES

Theoretical and experimental studies of laser produced, high-Z radiative plasmas were conducted. A theoretical model and computer code have been developed which include the effects of index of refraction, bremsstrahlung, recombination radiation, line radiation, single fluid shock hydrodynamics, separate kinetic temperatures for electrons and ions, and electron thermal conductivity. Its validity extends to highly nonequilibrium regimes such as the "time dependent corona" regime. Computer calculations have been performed which predict that large fluxes of X-rays can be gener-

ated by placing high-Z targets in the laser focus, with efficiencies in excess of 20 percent for converting laser light into X-rays being feasible at 10^{14} watts/cm^2 of laser light incident over 1 nanosecond. The experiments were performed using 10–100 joule, 1–2 nanosecond, 1.06 micron pulses generated with Battelle's HADRON/CGE VD-640 neodymium-doped glass laser, isolated from backscattered light by a special exploding mirror surface. The X-ray yield was measured with several techniques, including scintillator detectors, material damage, micro-calorimeter, scintillator camera, and thermoluminescence detectors. Conversion efficiencies of laser light into X-rays of at least 10 percent, probably 15–20 percent, and possibly higher were obtained with iron slab targets oriented at 45° with respect to the incident beam. The X-ray yield above 1 keV is about 5 percent of the incident laser light.

I. INTRODUCTION

Progress in the development of high power lasers during the past several years has opened the door to several new areas of research. The best known, of course, is the remarkable possibility of achieving controlled thermonuclear fusion by means of laser heated plasmas.

There is a second and newer application of high power lasers, however, which from the point of view of basic laser and plasma physics is equally exciting. The new problem is to generate an intense X-ray source using lasers. The simplest approach is to place a small particle in the focus of a high power laser or array of high power lasers, and thereby heat it to such a high temperature that the energy it radiates lies in the X-ray regime.

There are many points of similarity between the X-ray problem and the fusion problem. Both, for example, involve the laser heating of plasmas to the multikilovolt regime. But there is an important difference. The fusion work is mostly directed to the heating of fusionable materials, which by nature have a low atomic number, Z. The X-ray work, on the other hand, involves the heating of high-Z materials, which are far more effective in converting laser light into X-rays.

The research reported here has conclusively demonstrated that X-rays can be generated in sufficient quantities and in an appropriate spectral range to satisfy a number of important requirements for laboratory X-rays.

In the early phase of the study, the Battelle laser-generated plasma computer code FLASH was generalized to acount for time dependent ionization, and conversion efficiencies greater than 20 percent of laser light into X-rays were calculated assuming certain initial plasma conditions. At the same time, a HADRON/CGE VD-640 laser was installed by Battelle-Columbus, and a special isolator device was developed to eliminate the troublesome problem of glass damage caused by amplification of laser light backscattered from targets.(1)

In the next phase, the total X-ray yield and effective temperature were studied with 1 nanosecond laser pulses preceded by a variety of "feet" (i.e., prepulses) ranging from approximately 1 to 15 nanoseconds. The purpose here was to identify the prepulses that would establish optimum initial plasma profiles when the laser beam was focused on particular solid targets. In addition to the foot study, tests were conducted to establish the feasibility of preventing debris from the laser generated plasma from striking X-ray irradiation samples.

The results were extremely successful. X-rays with an energy above ~1 keV were routinely delivered, behind a beryllium debris shield, at sufficiently high fluxes to vaporize lead over an area of several cm^2. Efficiencies of ~5 percent for converting laser light to X-rays above 1 keV were obtained. The overall conversion efficiency of laser light to X-rays that was obtained was at least 10 percent, probably 15–20 percent, and possibly 30–40 percent. Most remarkably, these results were all obtained using 1–2 nanosecond laser pulses with less than 100 joules total energy. There is no question that these conversion efficiencies, which are already satisfactory, could be increased with the use of larger laser pulses.

The plasmas most effective for X-ray production consist of high-Z materials raised to the multikilovolt regime. The dynamics of a high-Z plasma and its radiative output involve a variety of collisional and radiative processes in addition to the usual phenomena that occur in low-Z plasmas. The new processes make possible higher conversion efficiencies, but also add considerable complexity to the problem. In view of this complexity it will be valuable, before discussing the theoretical and experimental work in detail, to establish the basic story of what happens when a high intensity laser pulse strikes a high-Z target: a discussion of the basic phenomenology is provided in the next two sections, where for definiteness, 1000 joules of pulsed neodymium laser light are assumed.

II. MACROSCOPIC CHARACTERIZATION

The first problem to consider is to insure that laser light is admitted into the plasma and not reflected away at the surface. Whenever the laser frequency ω_L is less than the plasma frequency $\omega_p = (4\pi n_e e^2/m)^{1/2}$ of the target plasma, the incident light is reflected. If the reverse is true, the light will enter the plasma. The critical electron density at which the plasma frequency equals the frequency of neodymium laser light is 10^{21} cm^{-3}, so that to avoid reflection

$$n_e \leq 10^{21}\ \text{cm}^{-3} \qquad (1)$$

This description of light reflection is naive and not always true, but it is a useful introductory statement of a problem that must be ultimately dealt with.

The second problem to consider is whether the laser light is absorbed by the plasma. In order to insure a high conversion efficiency of laser light into X-rays, most of the light must be absorbed rather than transmitted through the plasma. This condition imposes a lower bound on the electron density of about 10^{19} or 10^{20}. Thus, there is a working range of one or two factors of ten of electron density in which the laser light enters the plasma without being reflected and is also mostly absorbed before passing through.

Now where within this working range is it most desirable to operate? The answer is provided by the objective of maximizing the X-ray yield. Since all of the processes known to contribute to X-radiation, namely bremsstrahlung, recombination radiation and line radiation, increase with the square of electron density, it is desirable to work as close as possible to the upper end of the working range. This establishes 10^{21} as a sort of "favorite" electron density for X-ray production.

Now what should the plasma size be? This is established by heat capacity considerations based on complete absorption of the 1000 joules of incident laser

light. The characteristic volume and side length of a plasma, of electron density 10^{21}, that lies in the multikilovolt regime with 1000 joules of absorbed energy are

$$L^3 \sim 10^{-3}\ \text{cm}^3, \tag{2}$$

$$L \sim 10^{-1}\ \text{cm}. \tag{3}$$

This is a reasonable approximation for plasmas of any atomic number, Z.

It is now possible to determine what the pulse length of the laser should be. This parameter is established by the characteristic hydrodynamic expansion time of a 0.1 cm thick multikilovolt plasma, which is $\sim 10^{-9}$ seconds. The approximation is valid for plasmas of any n_e and Z within a factor of 3 or so. If a pulse substantially longer than a nanosecond is used, the plasma will expand and go transparent during the irradiation, and will convert the absorbed energy into X-rays with a reduced efficiency. A shorter pulse, on the other hand, is probably acceptable, but there is usually no reason to make the problem more difficult by employing a pulse which is unnecessarily short. The appropriate pulse width of the laser is thus

$$\tau_L \sim 10^{-9}\ \text{sec}. \tag{4}$$

What about heat conduction and temperature uniformity? Heat is conducted in the laser plasma mainly by electron thermal conductivity. This process is similar to the conductivity of an ordinary gas except that the carrier particles are electrons rather than atoms. Calculations show that electron thermal conductivity will generally render the electron temperature uniform within a nanosecond if the final electron temperature is greater than ~ 5 keV, but will have difficulty in doing so if the final electron temperature is only 1 or 2 keV. When the conductivity fails, other processes, such as shock heating and the tendency of the incident light to be transmitted through hot regions and absorbed in cold regions, will usually step in and establish a reasonably uniform temperature. Reradiated energy, on the other hand, is not an effective agent for temperature equalization. Most of its escapes from the plasma, except at low temperatures.

We have thus far arrived at a self consistent set of laser and macroscopic plasma parameters for maximizing X-ray production for the case of 1000 joules of neodymium laser light. But neither the numbers for their stated limitations are absolute. For example, it appears possible to heat plasmas with electron densities greater than 10^{21} by means of a two step process, the first step of which was pointed out by Dawson, Kaw and Green.[2] The idea is that no plasma is uniform, so that reflection of an external laser beam at the critical density point entails a two way passage of the light through an outer skin with an electron density ranging from 0 to 10^{21}. This "underdense" portion of the plasma is often capable of absorbing most of the incident energy, which is then partly transported to the "overdense" portion of the plasma by electron thermal conductivity. Thus, the numbers obtained above are mainly logical guidelines for an initial study.

III. MICROSCOPIC CHARACTERIZATION

In any case, we are now in a position to characterize the microscopic nature of the plasma. The overriding feature in this realm is that the plasma particles are not in local thermodynamic equilibrium (LTE). One nanosecond is long enough for the electrons to equilibrate among themselves by coulomb collisions and be characterized by an electron kinetic temperature, T_e. Similarly, there is enough time for the ions to equilibrate among themselves at an ion kinetic temperature, T_i. But there is generally insufficient time for T_e and T_i to become equal. What usually happens is that the incident laser light is absorbed by the electrons, which rise in temperature relatively rapidly while slowly heating the ions by electronion collisions.

Now this in itself constitutes a breakdown of LTE. But it is a trivial aspect of its breakdown, both from an analytic point of view and from the point of view of X-ray production. This is not to say that it is unimportant. Indeed, in a fusion plasma it is of paramount importance, since the desired product—fusion energy—would be sharply supressed by a lagging ion temperature. But in the X-ray problem the desired product depends mainly on electron temperature, which is only slightly affected (in high-Z plasmas) if the ion temperature lags.

There is another aspect of the breakdown of LTE which has a far more serious effect on X-ray production. This is the question of whether or not the relative ion populations (i.e., the relative number, say, of 15, 16 and 17 times ionized tungsten) are governed by the Saha Equations, as they should be for a plasma in LTE. The importance of this question is due to the strong dependence of X-ray emission on ionization potential.

The Saha Equations may be written in the approximate form[3]

$$\frac{f_{s+1}}{f_s} = 3.0 \times 10^{39} \frac{(kT_e)^{3/2}}{n_e} \exp\left(-\frac{\chi_s}{kT_e}\right), \tag{5}$$

where f_s and f_{s+1} are the ion fractions that are s and $s+1$ times ionized, n_e is the density of free electrons, and kT_e is the electron temperature: χ_s is the ionization potential of the s times ionized ion. In this report, cgs units are used unless otherwise stated. In the case of a plasma which is optically thin, the ionization state described by the Saha Equations results from the competitive balance between collisional ionization by two-body electron-ion collisions, and recombination by so-called three-body recombination. The latter process is a radiationless three-body "collision" involving one ion and two electrons, in which one electron combines with the ion, while the other is scattered away with a direction and velocity which guarantees energy and momentum conservation. These processes are statistical inverse of one another (i.e., one transfonas into the other under time reversal); this is to be expected, since the Saha Equations pertain to an ion distribution which is in LTE.

The Saha Equations definitely break down. This may be seen by applying the following (very approximate) rule of thumb given by McWhirter[4]:

$$n_e \leq 10^{16} (T_e)_{eV}^{3/2}\ \text{cm}^{-3}. \tag{6}$$

The quantity $(T_e)_{eV}$ is the electron temperature expressed in electron volts. Whenever Equation (6) is satisfied, the Saha Equations break down and the ion distribution is out of equilibrium. This is generally the case in the present problem, since use of $T_e \geq 1000$ eV in Equation (6) gives $n_e \leq 3 \times 10^{26}$, which is easily satisfied by the key electron density 10^{21}. On a micro-

scopic level, the state of affairs that prevails when Equation (6) is satisfied is that the relative ion populations are determined by the competitive balance between collisional ionization— the same ionization process as in the Saha regime—and two-body radiative recombination, in which a free electron recombines with an ion and the excess energy and momentum are carried off by a photon. These processes are not statistical inverses of one another: the ionization process is purely collisional, whereas the recombination process involves a photon.

Now when Equation (6) is satisfied, the ion distribution is often still in a quasi-steady, though nonequilibrium, state. The ionization equations in this case are tractable as those for equilibrium, the main difference being that the Saha Equations are replaced by another set of quasi-steady equations, generally known as "Coronal Equilibrium" equations. The exact form of these equations depends on the formulas selected for the fundamental cross-sections. The Coronal Equilibrium equations implied by the formulas given in Section IV are

$$\frac{f_{s+1}}{f_s} = 3.3 \times 10^{-16}\left(\frac{1}{1+d}\right)\frac{\Delta_o(s)\,(kT_e)^{\frac{1}{2}}}{\chi_s^{1\frac{1}{4}}}\exp\left(-\frac{\chi_s}{kT_e}\right), \tag{7}$$

where $\Delta_o(s)$ is the number of electrons in the outer Bohr shell ($\Delta_o=1$ hydrogenlike ion, $\Delta_o=6$ for oxygenlike ions, etc.), d is a correction term, and the other quantities are defined as in Equation (5). The term "quasi-steady", as applied to Equations (5) and (7), refers to the fact that f_s's at any instant are specified by the instantaneous values of T_e and n_e.

Unfortunately, in a laser heated plasma, quasi-steady conditions do not always prevail. This may be established by a second rule of thumb, also given by McWhirter[4], which applied whenever Equation (6) is satisfied; this second rule of thumb states that quasi-steady conditions break down if the characteristic time for hydrodynamic expansion or contraction, τ_h, satisfies the relation

$$\tau_h \lesssim \frac{10^{12}}{n_e}. \tag{8}$$

If Equation (8) is satisfied, the plasma is in an extremely nonequilibrium state. To specify the instantaneous ionization state, it is necessary to know not only the local free electron conditions, but their entire past history as well! The only recourse in such a situation is to solve rate equations which include the principal microscopic processes that contribute to the ionization rate, and calculate the time development of the plasma from an initial state.

The ionization of a multikilovolt laser generated plasma requires the time dependent treatment. This may be seen by inserting the critical electron density 10^{21} in Equation (8). In the underdense plasma "skin," where $n_e < 10^{21}$, the full time dependent treatment is required, although in the overdense "core" (which can be heated by shocks and thermal conduction), a quasisteady treatment is generally valid.

IV. THEORETICAL MODEL

A theoretical model and computer code have been developed to predict the time development of a high-Z, radiative plasma interacting with a laser beam. The computer code is designated by the name FLASH, and is continually being extended and improved. The version to be discussed in this report is FLASH 3, which is one dimensional but accounts for the time dependence of ionization.

ABSORPTION AND REFLECTION

In the model for absorption and reflection of laser light, the light enters the surface of the plasma and penetrates, via the laws of geometrical optics, to the critical density point, where 100 percent reflection is assumed to occur: it then retraces its path and exits from the plasma. On the way in and on the way out it is assumed to be absorbed at the rate predicted by the Dawson and Oberman[5] microwave conductivity formula, suitably modified by the approximate index of refraction[6]

$$n = \left(1 - \frac{\omega_p^2}{\omega^2}\right)^{\frac{1}{2}}, \tag{9}$$

where ω_p is the plasma frequency. Thus, the beam intensity attenuates as $dI/dx = -\alpha I$, with the absorption coefficient given by

$$\alpha = 6.2 \times 10^{-25}\,\frac{n_i \overline{Z^*}\cdot\overline{Z^{*2}}\log\Lambda}{\omega^2\left(1-\frac{\omega_p^2}{\omega^2}\right)^{\frac{1}{2}}(kT_e)^{3/2}}\ \text{cm}^{-1}, \tag{10}$$

where

$$\omega_p^2 = 3.182 \times 10^9\, n_i \overline{Z^*}\ \text{sec}^{-2}. \tag{11}$$

The light which survives absorption during the two way passage constitutes reflection. In these formulas, n_i denotes ion density, T_e denotes electron temperature, and ω is the frequency of the laser light. The quantity $\overline{Z^*}$ is the mean ion effective charge, $\overline{Z^{*2}}$ is the mean square ion effective charge, and log Λ is the so-called Coulomb logarithm, which is generally set equal to 5 or 10 throughout a given problem. The justification for this extension of microwave absorption theory to the optical regime was provided by Mallozzi and Margenau[7], who showed that the primary physical process underlying the absorption of laser light is plasmas, namely free-free absorption (inverse bremsstrahlung), is the quantum analogue of the process which underlies classical microwave absorption: the formulas for free-free absorption and microwave absorption were shown to be identical when $h\nu << kT$.

CONSTITUTIVE EQUATIONS

The laser energy which is absorbed in each zone of the plasma is converted into electron kinetic energy. Now for a plasma in LTE, the energy which the electrons absorb is immediately partitioned, in a fixed and rate independent way, among the internal degress of freedom in each zone. However, in the present plasma, the conditions in each zone must be established by solving an appropriate set of rate equations. These equations are given next, and provide a time dependent link between the total energy density ϵ, the total pressure p, the kinetic electron and ion temperatures T_e and T_i, and the relative ion populations f_s.

The relative ion populations are described by the equations

$$\frac{df_0}{dt} = \bar{Z}^2 n_i(-f_0 S_0 + f_1\alpha_1 + \bar{Z}^2 n_i f_1\beta_1)$$

$$\vdots$$

$$\frac{df_s}{dt} = \bar{Z}^2 n_i(-f_s S_s - f_s\alpha_s - \bar{Z}^2 n_i f_s\beta_s + f_{s-1}S_{s-1} + f_{s+1}\alpha_{s+1} + \bar{Z}^2 n_i f_{s+1}\beta_{s+1})$$

$$\vdots$$

$$\frac{df_z}{dt} = \bar{Z}^2 n_i(-f_z\alpha_z - \bar{Z}^2 n_i f_z\beta_z + f_{z-1}S_{z-1}), \quad (12)$$

together with the normalization condition

$$\sum_{s=0}^{z} f_s = 1, \quad (13)$$

and the definition

$$\bar{Z}^2 = \sum_{s=1}^{z} f_s Z_s^2. \quad (14)$$

The quantity

$$Z_s = 0, 1, \ldots Z \quad (15)$$

and denotes effective ion charge. The coefficients S, α, and β appearing in Equations (12) account respectively for collisional ionization, radiative recombination, and three body recombination, and are given by

$$S(Z_s) = 4.9 \times 10^{-24} \frac{\Delta_0(Z_s)(kT_e)^{\frac{1}{2}}}{\chi^{3/4}(Z_s, g)} \exp\left(-\frac{\chi(Z_s, g)}{kT_e}\right), \quad (16)$$

$$\alpha(Z_s) = 1.5 \times 10^{-8}(1+d)\frac{\chi(Z_s - 1, g)}{(kT_e)^{\frac{1}{2}}}, \quad (17)$$

$$\beta(Z_s) = 1.6 \times 10^{-63} \frac{\Delta_0(Z_s - 1)}{\chi^{3/4}(Z_s - 1, g)(kT_e)^{5/2}} \quad (18)$$

In these formulas, $\chi(Z_s, g)$ denotes the ground state ionization potential of an ion of effective charge Z_s, and $\Delta_0(Z_s)$ is the number of electrons in the outermost occupied Bohr shell. The quantity d is a correction for dielectronic recombination.[6] The formulas for S and α are essentially those given in reference 4, except for d, and their use leads Equations (12) to reduce to the Coronal Equilibrium Equations (7) in the limit of low particle density and slow time variation. The formula for β was derived from S by requiring Equations (12) to reduce to the Saha Equations (5) in the limit of *high* particle density and slow time variation. This procedure leads to a low estimate for β: The reason is that Formula (16) underestimates S at high densities, since is ignores the existence of excited states.

The ionization equations given above must be solved simultaneously with the following equations for energy and pressure:

$$\epsilon = \epsilon_e + \epsilon_I + \epsilon_i, \quad (19)$$

$$p = \tfrac{2}{3}(\epsilon_e + \epsilon_i), \quad (20)$$

$$\epsilon_e = (3/2)\bar{Z}^2 n_i k T_e \quad (21)$$

$$\epsilon_i = (3/2) n_i k T_i \quad (22)$$

$$\epsilon_I = n_i \sum_{s=0}^{Z} f_s U_s = n_i \sum_{s=1}^{Z} f_s \sum_{j=1}^{s} \chi(Z_j = 1, g) + \text{Const.}, \quad (23)$$

$$\frac{d(\epsilon_e + \epsilon_I)}{dt} = -(\epsilon_e - \bar{Z}^2 \epsilon_i)\frac{1}{\tau_{ei}} + \left[\frac{\Delta(\epsilon_e + \epsilon_I)}{\Delta t}\right]_{\text{rerad.}} \quad (24)$$

$$\frac{d\epsilon_i}{dt} = (\epsilon_e - \bar{Z}^2 \epsilon_i)\frac{1}{\tau_{ei}}. \quad (25)$$

Equation (19) expresses the total density ϵ(ergs/cm³) as a sum of the electron and ion kinetic energy densities ϵ_e and ϵ_i, defined by the ideal gas formulas (21) and (22), plus the total ionization energy density ϵ_I. The latter quantity is defined in Equation (23) in terms of the ground state binding energies U_s per ion, and alternately, the ground state ionization potentials. The binding energies and ionization potentials can be supplied to FLASH as inputs, or calculated internally using a fundamental atomic model. Equation (20) express the pressure in terms of the total kinetic energy density, in accord with the ideal gas picture for pressure. Equation (24) gives the rate of change of $\epsilon_e + \epsilon_I$. The first term on the right side accounts for the change due to elastic electron-ion collisions: this term affects only ϵ_e. The second term accounts for the change in $\epsilon_e + \epsilon_I$ due to reradiation, and equals the negative of the total radiated power per cm³: this term in general affects both ϵ_e and ϵ_I. Equation (25) describes the change in ϵ_i, which is attributed to elastic electron-ion collisions.

These equations all ignore the potential energy between free electrons, the effect of inelastic collisions on ϵ_i, and the reabsorption of emitted radiation; they also assume that the ions are mostly found in the ground state. The quantity τ_{ei} which appears in Equations (24) and (25) is the electron-ion equipartition time, and is given by[7]

$$\tau_{ei} = 1.5 \times 10^{26} \frac{(kT_e)^{3/2} A}{n_i \bar{Z}^2 \log \Lambda}, \quad (26)$$

where A is the atomic mass number (A = 1 for hydrogen). This formula, as well as most others in FLASH 3 pertaining to collisional processes, is restricted to situations where T_i is not more than a few hundred times higher than T_e. Such conditions almost always apply.

CONDUCTION AND HYDRODYNAMICS

Heat conductions in FLASH 3 is accounted for by the following expression for the heat flow vector:

$$F = 1.3 \times 10^{-5} \frac{T_e^{5/2}}{\log \Lambda} \frac{\bar{Z}^2}{\bar{Z}^2} \nabla T_e \frac{\text{ergs}}{\text{cm}^2\text{sec}}. \quad (27)$$

This expression arises from electron thermal conductivity. Ion thermal conductivity is ignored.

Hydrodynamic motion is predicted by the hydrodynamic equations for single fluid one-dimensional motion. The Lagrangian method is employed, with shock computations stabilized by an "artificial viscosity" term. Energy density and pressure are given by the time dependent model described earlier, modified to allow for a changing n_i. Two terms are added to the right side of Equation (24) to allow for heat conduction and the absorption of laser light, which affect ϵ_e but not ϵ_I or ϵ_i. Heating due to compression and artificial viscosity is assigned to ϵ_e and ϵ_i (i.e., added to the right sides of

Equations 24 and (25) in proportion to the instantaneous ratio of ϵ_e to ϵ_i.

RERADIATION

The energy radiated by the plasma arises from three mechanisms: free-free radiation (bremsstrahlung), free-bound radiation (recombination radiation), and line radiation. FLASH 3 calculates the contribution from each process and assumes that the emitted radiation escapes from the plasma.

The free-free and free-bound radiation emitted into the spectral band $\Delta(h\nu)=h\nu_2-h\nu_1$ is given by

$$P_{ff}^2 = 1.2 \times 10^{-19} n_i^2 (kT_e)^{\frac{1}{2}} \left[\exp\left(-\frac{h\nu_1}{kT_e} \right) - \exp\left(-\frac{h\nu_2}{kT_e} \right) \right] \overline{Z^2} \cdot \overline{Z^2} \frac{ergs}{cm^3 sec}, \tag{28}$$

$$P_{fb}^2 = 5.5 \times 10^{-9} n_i^2 \frac{\overline{Z^2}}{(kT_e)^{\frac{1}{2}}} \sum_{s=1}^{Z} \sum_{n=1}^{6} f_{sn} \chi_n^2 (Z_s - 1) \frac{[2n^2 - \Delta_n(Z_s)]}{n} \exp\left(\frac{\chi_n(Z_s - 1)}{kT_e} \right)$$

$$\times \left(\exp \frac{-h\nu_1 H[h\nu_1 - \chi_n(Z_s - 1)] - \chi_n(Z_s - 1) H[\chi_n(Z_s - 1) - h\nu_1]}{kT_e} - \exp \frac{-h\nu_1 H[h\nu_2 - \chi_n(Z_s - 1)] - \chi_n(Z_s - 1) H[\chi_n(Z_s - 1) - h\nu_2]}{kT_e} \right) \frac{ergs}{cm^3 sec}, \tag{29}$$

where $\Delta_n(Z_s)$ is the number of n*th* shell electrons, $\chi_n(Z_s-1)$ is the ionization potential of an electron captured into that shell (the capture decreases Z_s by 1), and H is the "Heaviside" step function, defined by

$$H(x) = 0, x < 0,$$
$$H(x) = 1, x \geq 0. \tag{30}$$

Equations (28) and (29) are the usual formulas for free-free and free-bound radiation found in the literature[9] except that integrations over $h\nu$ have been performed, with Gaunt factors set equal to unity. The summation over n in Equation (29) extends over the first six shells, which are the ones most likely to influence two-body recombination.

Line radiation is given by

$$P_L = 6.4 \times 10^{-24} n_i^2 \frac{\overline{Z^2}}{(kT_e)^{\frac{1}{2}}} \sum_{s=0}^{Z} f_s F_s \exp\left(-\frac{\chi_r(Z_s)}{kT_e} \right) \frac{ergs}{cm^3 sec}, \tag{31}$$

where $\chi_r(Z_s)$ is a characteristic excitation energy for the *sth* ion species and F_s is a characteristic absorption oscillator strength. Equation (31) is based on a model where each ion species emits a single spectral line of photon energy $h\nu=\chi_r(Z_s)$, which is produced when ground state ions suffer inelastic two-body collisions with electrons and the excited states subsequently decay; the plasma is assumed optically thin to the emitted radiation. This picture of line radiation is admittedly approximate and lacking in fine structure. However, when combined with the FLASH time dependent ionization model, the frequency averaged line emission is a substantial improvement over what might be calculated with either the Saha or Coronal Equilibrium ionization models. Work is underway to develop a more detailed model for line radiation, including self absorption effects.

V. SAMPLE CALCULATIONS

The purpose of this Section is to present the results of two selected FLASH 3 calculations (FIGS. 12-23 and Tables 3 and 4). The input parameters for these computers runs (1 and 2) are given in Table 1, together with the input parameters of nine additional runs, which are reported in detail in the Final Report (Volume I) cited at the end of this specification. The computer runs cover two materials, three laser power densities, two laser wavelengths, and three initial plasma profiles. The problems are all one-dimensional, with the laser beams normally incident on infinite plasma slabs at uniform initial temperatures of 8.6 electron volts and with initial ion density profiles which are linear. These profiles are given in Table 2.

The main purpose in choosing these problems as the first to be analyzed was to illustrate the effect on X-ray production of basic interaction phenomena such as conduction and time dependent ionization: thus, simple slabs were studied rather than a spread of different target geometries. Another intention was to vary crucial parameters corresponding to tuneable laboratory quantities such as laser power density and the initial plasma profile. The latter quantity is related to the ionizing prepulse which strikes a solid target before arrival of the main pulse. One might wish that more materials were run. However, iron (Z=26) and calcium (Z=20) both yield high conversion efficiencies, and the basic plasma equations promise similar behavior for higher Z targets if slight changes in initial plasma profiles are made: the main difference is that harder X-ray spectra are generally attainable with higher Z targets.

An analysis of the computer runs and a comparison with earlier work [10,11,12] will be presented in Section VII. The runs will also be employed in interpreting the experimental results which are presented there.

TABLE 1.

	PARAMETERS FOR COMPUTER RUNS										
	1	2	3	4	4	6	7	8	9	10	11
Material	Iron	Iron	Calcium	Calcium	Calcium	Calcium	Calcium	Calcium	Calcium	Calcium	Calcium
Wavelength (microns)	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	10.6
Laser Pulse Width(nanoseconds)	1	1	1	.5	.5	.75	1	1	1	1	.1
Laser Power Density (watts/cm²)	1.05×10^{14}	1.05×10^{14}	1.05×10^{14}	1.05×10^{14}	1.05×10^{14}	1.05×10^{13}	1.05×10^{15}	1.05×10^{14}	1.05×10^{13}	1.05×10^{14}	1.05×10^{14}

TABLE 1.-continued

PARAMETERS FOR COMPUTER RUNS

	1	2	3	4	4	6	7	8	9	10	11
Initial Plasma Profile	A	A	A	A	A	A	B	B	B	C	A
Ionization Dynamics	Time Dep.	Equil	Time Dep.	Equil	Equil	Time Dep.	Time Dep.	Time Dep.	Time Dep.	Time Dep.	Time Dep.
Conduction	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes

TABLE 2.

INITIAL PLASMA PROFILES FOR COMPUTER RUNS

Plasma Profile	Slope (ions/cm³ per cm)	Thickness (cm)
A	5.1×10^{21}	0.030
B	5.1×10^{20}	0.30
C	1.02×10^{20}	1.50

TABLE 3

NONEQUILIBRIUM IRON CALCULATION: TIME-DEPENDENT IONIZATION

Time integrated reradiated energies as percent of time integrated input.
Incident laser flux = 1.05×10^{14} watts/cm²
Wavelength = 1.06 microns
Initial conditions: Plasma profile A
Computer Run 1, Figs. 12–17

Spectral Region, keV	Free-Free, %	Free-Bound, %	Line, %	Sum Over Processes, %
0.0 – 0.5	0.04	0.01	3.71	3.76
0.5 – 1.0	0.02	0.01	1.89	1.92
1.0 – 2.0	0.03	0.03	1.28	1.34
2.0 – 4.0	0.03	0.04	0	0.07
4.0 – 8.0	0.02	0.02	0.01	0.05
8.0 – 16.0	0.00	0.01	0	0.01
16.0 – 1024	0.00	0.00	0	0.00
Total	0.14	0.12	6.89	7.15

(a) Time = 135 Picoseconds

Spectral Region, keV	Free-Free, %	Free-Bound, %	Line, %	Sum Over Processes, %
0.0 – 0.5	0.07	0.01	3.96	4.04
0.5 – 1.0	0.05	0.03	2.30	2.38
1.0 – 2.0	0.06	0.06	2.76	2.88
2.0 – 4.0	0.06	0.13	0	0.19
4.0 – 8.0	0.03	0.06	0.12	0.21
8.0 – 16.0	0.01	0.01	0	0.02
16.0 – 1024	0.00	0.00	0	0.00
Total	0.28	0.30	9.14	9.72

(b) Time = 265 Picoseconds

Spectral Region, keV	Free-Free, %	Free-Bound, %	Line, %	Sum Over Processes, %
0.0 – 0.5	0.13	0.02	4.70	4.85
0.5 – 1.0	0.09	0.06	2.71	2.86
1.0 – 2.0	0.11	0.13	4.39	4.63
2.0 – 4.0	0.10	0.29	0	0.39
4.0 – 8.0	0.05	0.13	0.32	0.50
8.0 – 16.0	0.01	0.03	0	0.04
16.0 – 1024	0.00	0.00	0	0.00
Total	0.49	0.66	12.12	13.27

(c) Time = 412 Picoseconds

Spectral Region, keV	Free-Free, %	Free-Bound, %	Line, %	Sum Over Processes, %
0.0 – 0.5	0.19	0.02	11.00	11.21
0.5 – 1.0	0.17	0.06	2.14	2.37
1.0 – 2.0	0.15	0.22	4.33	4.70
2.0 – 4.0	0.14	0.50	0	0.64
4.0 – 8.0	0.09	0.20	0.81	1.10
8.0 – 16.0	0.03	0.04	0	0.07
16.0 – 1024	0.00	0.00	0	0.00
Total	0.77	1.04	18.28	20.09

(d) Time = 1000 Picoseconds

TABLE 4.

Time integrated reradiated energies as percent of time integrated input.
Incident laser flux = 1.05×10^{14} watts/cm²
Wavelength = 1.06 microns
Initial conditions; Plasma profile A
Computer Run 2, FIGS. 18 – 23

Spectral Region, keV	Free-Free, %	Free-Bound, %	Line, %	Sum Over Processes, %
0.0 – 0.5	0.04	0.01	0.37	0.42

TABLE 4.-continued

Time integrated reradiated energies as percent of time integrated input.
Incident laser flux = 1.05×10^{14} watts/cm²
Wavelength = 1.06 microns
Initial conditions: Plasma profile A
Computer Run 2, FIGS. 18 – 23

0.5 – 1.0	0.02	0.02	0.01	0.05
1.0 – 2.0	0.03	0.05	0.00	0.08
2.0 – 4.0	0.03	0.16	0	0.19
4.0 – 8.0	0.02	0.05	0.00	0.07
8.0 – 16.0	0.00	0.59	0	0.59
16.0 – 1024	0.00	0.02	0	0.02
Total	0.14	0.90	0.38	1.42

(a) Time = 137 Picoseconds

Spectral Region, keV	Free-Free, %	Free-Bound, %	Line, %	Sum Over Processes, %
0.0 – 0.5	0.09	0.02	0.77	0.88
0.5 – 1.0	0.06	0.05	0.01	0.12
1.0 – 2.0	0.07	0.12	0.01	0.20
2.0 – 4.0	0.06	0.41	0	0.47
4.0 – 8.0	0.03	0.15	0.00	0.18
8.0 – 16.0	0.00	1.43	0	1.43
16.0 – 1024	0.00	0.04	0	0.04
Total	0.31	2.22	0.79	3.32

(b) Time = 277 Picoseconds

Spectral Region, keV	Free-Free, %	Free-Bound, %	Line, %	Sum Over Processes, %
0.0 – 0.5	0.18	0.04	1.23	1.45
0.5 – 1.0	0.11	0.12	0.03	0.26
1.0 – 2.0	0.13	0.25	0.03	0.41
2.0 – 4.0	0.11	0.80	0	0.91
4.0 – 8.0	0.05	0.26	0.01	0.32
8.0 – 16.0	0.01	2.51	0	2.52
16.0 – 1024	0.00	0.07	0	0.07
Total	0.59	4.05	1.30	5.94

(c) Time = 428 Picoseconds

Spectral Region, keV	Free-Free, %	Free-Bound, %	Line, %	Sum Over Processes, %
0.1 – 0.5	0.31	0.07	1.00	1.38
0.5 – 1.0	0.17	0.26	0.11	0.54
1.0 – 2.0	0.20	0.48	0.15	0.83
2.0 – 4.0	0.17	1.44	0	1.61
4.0 – 8.0	0.10	0.39	0.00	0.49
8.0 – 16.0	0.03	3.44	0	3.47
16.0 – 1024	0.00	0.17	0	0.17
Total	0.98	6.25	1.26	8.49

(d) Time = 1000 Picoseconds

VI. DESCRIPTION OF EXPERIMENTS

The Laser

The experiments were performed with 1.06μ wavelength laser pulses generated with Battelle's HADRON/CGE VD-640 neodymium-doped glass laser. This instrument consists of a Q-switched oscillator followed by six amplifying stages. The final stage contains a 64 mm diameter rod. The capability of the laser ranges from 100 joules in 30 ns. This range of outputs is achieved by generating a standard 4 joule, 30 ns pulse with the oscillator and passing it through a "pulse clipper," which is located between the oscillator and the first amplifying stage. The pulse clipper consists of a laser triggered spark gap which switches a Pockels cell on for 1–2 ns near the peak of the 30 ns pulse. The width of the clipped pulse is essentially maintained as it passes through the amplifiers.

Laser Modifications

The first experiments were frustrated by the problem of damage to laser rods caused by laser light backscattered from the target. This problem was well known from laser generated thermonuclear fusion work, and had forced many experiments to be performed at power levels far below the capability of the available laser systems. (13) In the VD-640 laser operating in the 100 joule/1 nanosecond mode, glass damage will occur if as little as 1/100 joule is reflected back along the optical path by the target. The 1/100 joule pulse, although distributed over approximately 30 cm^2 of glass when it reenters the last amplifier, will converge and be amplified as it retraces the optical path, and at some point will exceed the 10 $joule/cm^2$ damage threshold as it funnels through smaller and smaller rods. There are certain combinations of pulses and targets for which the backscattered light is acceptably low, but this does not solve the problem. A malfunction in equipment might still deliver a dangerous pulse, and in any case it is undersirable to be limited in the experiments that can be performed.

It would appear that the laser could be protected most simply by introducing an electro-optical shutter after the last stage. The shutter would transmit the forward pulse but be switched off before the return of the back-scattered pulse. Unfortunately, the construction of Kerr or Pockels cells large enough to handle large diameter beams is very difficult and expensive. In a somewhat more attractive scheme a large multipass Faraday rotator and polarizers are used.(14) But even Faraday rotators have drawbacks for large lasers, owing to the difficulty of establishing the large volume, strong, uniform magnetic fields which are required.

To avoid these difficulties, a new method for isolating Q-switched lasers was developed. (1) The technique is readily applicable to Q-switched lasers of any aperture, power and pulse width.

Referring now to FIG. 24, a key element is a special mirror 14 designed to be highly reflecting to light incident from the front 17 and to be destroyed by light incident from the back 27. The mirror coating 14 consists of high reflectivity copper 30 deposited over high absorptivity germanium 28.

An incident pulse 15 strikes a beamsplitter 22, which transmits most of the pulse 16, 17 to the copper mirror 14 and reflects a portion 25 through the long leg 25, 26, 27 to the mirror backside. The path length of the back leg is sufficiently long that the main pulse 17 completely reflects off the front of the special mirror 14 before the small rerouted portion 27 strikes it from the back. The small pulse 27 blows the mirror film 30 off the glass plate 36, and the light scattered back along the optical path strikes a cloud of mirror coating debris.

A laser isolator based on these principles has been designed and installed between the last two stages of the Battelle laser. The device includes a precautionary feature 43, in which two lenses (46 schematically) are inserted between the beamsplitter 22 and the special mirror 14 for the purpose of focusing the beam through a small iris 47 and recollimating it. The iris 47 is enclosed in a vacuum to suppress attenuation from air breakdown, and serves the function of limiting the solid angle of acceptance of light which may be diffusely scattered into the return path by the debris cloud. In all tests conducted thus far, light backscattered by the target was attenuated by a minimum of 99 percent in passing through the isolator. The 2 or 3 db attenuation in the forward direction is easily recovered by increasing the amplification of the final stage. One drawback of this system is that a laser pulse entering the isolator at a level which is unexpected low by a factor of four or more will yield insufficient energy in the back leg to blow off the mirror. But the laser is not likely to suffer reflection damage at these lower pulse levels. In any case, additional mirror development is expected to substantially improve the low pulse limit for mirror blowoff, and the problem can be eliminated altogether by inserting a supplemental nonlinear absorber 40 to protect against the weaker backscattered pulses, or else at a scarifice of damage to the mirror blank, by vaporizing the mirror using an electrical discharge as in FIG. 25. In the present system the mirror blanks are undamaged and can be recoated at reasonable cost.

The device described above is actually a highly versatile instrument which is capable of simultaneously serving many functions besides isolation. These include beam homogenization, superradiance suppression, and divergence sharpening.

The special mirror 14, for example, serves a secondary function of suppressing hot spots in the laser beam. This is accomplished by placing the front surface of the mirror at a position where the average flux approaches the damage threshold of the reflective coating. The hot spots will exceed the damage threshold and be reduced in energy, which promotes a more homogeneous beam and helps protect downstream laser rods from hot spot damage. The same effect affords protection from accidently large pulses.

The lens-iris-lens combination 43 can be used to limit the beam divergence, and do it in such a way that it actually provides some isolation by itself and suppresses amplified spontaneous emission as well. Light backscattered from the main pulse by the plasma will be relatively diffuse and be stopped in large part by an iris 47 designed to barely accomodate the normal divergence. Amplified spontaneous emission also has a relatively high divergence and will be sharply reduced in passing through the iris 47. Use of the iris in the indicated way can replace procedures based on separating the laser amplifiers by long distances from one another and from the target.

The varied uses for the isolator components suggests that its placement at a number of strategic points in an amplifier chain can alleviate many of the problems of multistage high gain systems. As a byproduct, the lens-iris-lens combination 43 can serve as a beam expander and collimater to step up the beam diameter between stages. Use of collimated beams in the laser rods can reduce the degradation of beam divergence by pump induced inhomogeneities.

Further details of the laser modifications discussed above are included in the U.S. Patent application of Philip J. Mallozzi, Harold M. Epstein, Craig T. Walters, David C. Applebaum, and William T. Gallagher for Backscatter Isolation, Ser. No. 246,161, filed Apr. 21, 1972, now U.S. PAT. No. 3,778,585, issued Dec. 11, 1973.

One of the objectives of the present study was to assess the feasibility and cost of building a large parallel rod multistage laser for X-ray production. The study showed that problems such as isolation and amplified spontaneous emission can be solved at a reasonable cost, and that the critical factor in the overall cost is the output energy that can be delivered from each final

stage in 1-2 ns pulses. As part of the evaluation of the output per stage, two 100 joule, 1-2 nanosecond pulses were delivered through the last stage of the Battelle laser, with the pulses spaced sufficiently in time to prevent glass damage. This doubled the usual short pulse capability of the Battelle laser, since the pulses were emitted along separate optical paths. This permits them to be simultaneously delivered to targets after appropriate time delays.

X-Ray Production

Once the isolation problem was solved, laser pulses with energies ranging from ~10 to 100 joules and a pulse width of ~1½ nanosecond were focused down on a variety of targets, including spheres, slabs, and wires, and the emitted X-rays were observed. The basic experimental configuration is outlined in FIG. 1, which shows the case of a thick slab irradiated at a 45° angle of incidence. The focal length of the lens is 7 cm, and it focuses the beam down to a spot size of ~100 to 200 microns diameter. Allowing for the ~15 percent energy loss suffered in passing through a lens and chamber window, this corresponds to a range of power density centering on 10^{14} watts/cm². The same range was employed in the computer calculations.

This program has concentrated on slab targets, in spite of the fact that the best results can probably be achieved with special target designs. [10] This approach was useful in gaining basic data. It also proved that even simple targets can yield high conversion efficiencies, at least for the case of soft X-rays.

The first experiments, performed with infinitely thick slabs, produced a tiny flux of X-rays on the second shot. But, when slabs thought to be optimally thick were used, no X-rays were detected. The reason for this mysterious behavior was that several tenths or hundredths of a joule of amplified spontaneous emission was being delivered to the target over an $\sim 10^{-4}$ second interval before the arrival of the main pulse. This amount of energy is sufficient to vaporize a parcel of matter designed to reach multikilovolt temperatures with the 100 joule main pulse, and 10^{-4} seconds is sufficient time for the vapor to essentially disappear.

Recognizing this effect, the experiments in this study were designed for thick slabs and many of the optimizing effects associated with using a variety of think targets were simulated with prepulses. The prepulses or "feet" that were tried ranged in pulsewidth from 1 to 20 ns, and struck the surface at power densities of about 10^{11} watts/cm². The function of the foot is to produce a plasma so that the main pulse strikes a plasma rather than the solid. The thickness and density profile of the initial plasma can to a large extent be controlled by tuning the foot parameters. A typical combination of foot and main pulse is shown in FIG. 2.

X-Ray Diagnostics

The characteristics of the emitted X-rays were measured by several diagnostic methods, including differential absorption foil techniques, thin film and thinister resistance calorimeters, material damage threshold calorimeters, a bent crystal X-ray spectrometer, calibrated scintillation detectors, thermoluminescence detectors, and X-ray pinhole cameras. The purpose was to assess the yield and time integrated spectrum and to provide information for comparisons with the models.

Differential Foils

In the studies made with differential foils, the X-ray power was usually monitored by two scintillation detectors placed at angles nearly perpendicular to the target face (c.f. FIG. 1). In addition, the laser power and foot power were simultaneously recorded for each shot. Various thicknesses of beryllium, carbon, and aluminum foils were placed in front of the scintillators to block the reflected laser light and to serve as differential X-ray absorption foils. The ratio of X-ray transmission through foils of two different thicknesses was reduced to a "bremsstrahlung temperature" by the technique developed by Jahoda, et. al., [15] and was indentified with the plasma electron temperature.

Now this technique is strictly applicable only to a spectrum consisting of bremsstrahlung and the high frequency tail of the free-bound continuum. But when proper care is exercised in interpreting the results, the technique is also valid in situations such as the present one, where line emission is important.

The relative transmission through several thicknesses of beryllium of the X-rays emitted from an iron slab target with ~40 joules incident on 10^{-4} cm² is shown in FIG. 26. A low resolution spectrum derived from the transmission curve has the shape of a plasma bremsstrahlung distribution curve with KT ~0.8 keV, except in the strong line regime below 1.25 keV (FIG. 27). This indicates that consistent results can be obtained with two foil temperature measurements when care is exercised in selecting foils of the proper thickness. A derivation of the spectral distribution function $S(h\nu)$ and the range of thicknesses over which the Jahoda temperature will be relatively independent of the choice of foils is given next.

The absorption cross section $\rho\mu$ of beryllium may be approximated by

$$\rho\mu(h\nu) = 980(h\nu)^{-3}\text{cm}^{-1}, \tag{32}$$

where $h\nu$ is the photon energy in keV. The energy detected behind a thickness x of beryllium is thus

$$E(x) = \int_0^\infty S(h\nu)\exp[-\rho\mu(h\nu)x]d(h\nu)$$
$$= \int_0^\infty S(h\nu)\exp[-980(h\nu)^{-3}x]d(h\nu), \tag{33}$$

from which we derive

$$\frac{dE(x)}{dx} =$$
$$-\int_0^\infty \frac{S(h\nu)}{x}\{980(h\nu)^{-3}x\exp(-980(h\nu)^{-3}x)\}d(h\nu). \tag{34}$$

Now for each foil of thickness x there corresponds a photon energy $h\nu_x$ determined by

$$980(h\nu_x)^{-3}x = 1. \tag{35}$$

The quantity in the curly brackets has a rather sharp maximum at that energy, so that

$$\frac{dE(x)}{dx} \approx -\frac{a}{x} S(h\nu_x), \quad (36)$$

which may be written

$$S(h\nu_x) \approx -\frac{1}{a} \frac{dE(x)}{dx} x. \quad (37)$$

This equation provides the basis for deriving FIG. 27 from FIG. 26 and establishes that the range of foil thicknesses corresponding to the plasma bremsstrahlung shaped portion of FIG. 27 ($1.3 < h\nu < 3$ keV) is ~ 1 to 10 mils. Consistent two foil temperatures can be obtained with foils in this range. However, extrapolations of the bremsstrahlung curve to determine total conversion efficiencies are unreliable and were not used here.

Bent Crystal X-Ray Spectra

The spectral lines were measured with a bent crystal X-ray diffraction spectrometer. A bent KAP crystal with a 3 inch radius was positioned at about 35 cm from the X-ray source. The X-rays were diffracted from the convex face of the crystal onto a strip of Kodak NS 2T film with a 3.5 inch radius of curvature. The spectrometer chamber was optically isolated from the target chamber by a 3000 A paraline window coated with 1000 A of aluminum on each side.

Calorimetry. Three calorimetric techniques were employed in this study: thermoluminescence detectors (TLD's), material damage threshold calorimeters, and nickel resistance thermometers.

The TLD's were tried first, but were completely saturated at reasonable distances by the high intensity of soft X-rays. This problem was eliminated by placing large thicknesses of absorber over the TLD's, and with 10 mils of beryllium the TLD's agreed within a factor of two with results obtained from calibrated scintillators. This corroborated the hard X-ray results. But it rendered the method useless for soft X-rays, which were the main component of the output.

A technique which proved more useful was the Material Damage Threshold Calorimeter shown in FIG. 28. This new technique, which relates X-ray fluence to vaporization of a thin lead film, was developed for the special purpose of providing lower bound conversion efficiencies for nanosecond pulses of soft X-rays. A frequently employed configuration consists of a 2000 A lead film deposited on a glass substrate and placed behind a 1 mil beryllium debris shield. The effect of thermal radiation from the beryllium shield has been shown to be negligible. A 2000 A lead thickness was preferred because it absorbed a reasonable fraction of the X-rays and was sufficiently thin to thermally equilibrate in a nanosecond. Laser irradiations of this film with 1–2 ns pulses showed that complete film removal occurs only when the absorbed laser fluence is sufficient to vaporize the entire thickness of lead. The threshold amount of absorbed X-ray energy required to vaporize the lead will essentially be the same, since the thermal equilibration time is less than the pulse width.

VII. ANALYSIS OF RESULTS

The purpose of this section is to analyze and compare the results of the computer calculations and the experiments.

The experiments were performed for a range of incident power densities from 10^{13} to $\sim 2 \times 10^{14}$ watts/cm^2 and for a variety of elements, including iron and calcium. The computer calculations were performed for the same range of power densities, and also covered iron and calcium.

The input conditions in the computer calculations differed in a few respects from those actually employed in the experiments. The experiments were mostly performed with a peaked pulse focused at 45° incidence to a finite spot on a slab, whereas the calculations dealt with a square wave pulse covering an infinite plane at normal incidence. But these differences turn out to be immaterial for most of cases studied.

The key to relating theory with experiment lies in the foot. When the role of the foot is included, the two methods of study fall into basic agreement, both in the overall prediction of conversion efficiencies and in the point by point description of how these efficiencies come about. An approximate model for the plasma created by the foot is given in the Appendix. The model assumes that the plasma is optically thick to laser radiation and to its own radiation, in contrast to its behavior during the main pulse. It is intended for high-Z slabs which are irradiated by neodymium laser light at an intensity of $I_f = I_{foot}$ of $\sim 10^9$ to 10^{13} watts/cm^2, with pulse widths ranging from approximately 1 to 20 nanoseconds or more.

The model given in the Appendix for the foot plasma has been used to compute the average ion density $(n_i)_{av}$, the temperature T, and the thickness d of the initial plasma profile for iron as a function of the intensity I_f and pulsewidth τ_f of the foot. The results are given in FIGS. 5 and 6. Now the computed thicknesses of most of the initial plasmas generated in the experiments are somewhat greater than the ~0.01 to 0.02 cm focal spot diameter. This and other geometrical aspects of the experiments can be dealth with in an approximate way by assigning a linear density gradient, or slope, to each of the initial plasmas. A reasonable first estimate is to assign an ion density slope of $(n_i)_{av}/d$ to the plasma with $(n_i)_{av}$ taken from FIG. 5 and d taken from FIG. 6. Slopes calculated on this basis are given in FIG. 7.

A large number of experiments were performed with iron at an incident power density of $\sim 10^{14}$ watts/cm^2 for the main pulse. The foot employed in most of these experiments was $\sim 10^{11}$ watts/cm^2 over ~10 nanoseconds. The corresponding parameters for the initial plasma profile are found from FIGS. 5–7.

$$N_i \sim 4 \times 10^{18} \text{ ions/cm}^2 \quad (1\text{-a})$$

$$(n_i)_{av} \sim 1.5 \times 10^{20} \text{ ions/cm}^3 \quad (1\text{-b})$$

$$\text{Slope} \sim 6 \times 10^{21} \text{ ions/cm}^3 \text{ per cm} \quad (1\text{-c})$$

$$d \sim 0.025 \text{ cm} \quad (1\text{-d})$$

The calculated value of N_i implies that $\sim 10^{15}$ ions are located in the focal volume and heated by the main pulse. This quantity of matter will be raised to an electron temperature of ~5 keV upon absorbing a 100 joule main pulse, so that the foot is well "tuned" with respect to "selecting" an initial plasma with an optimum heat capacity. The calculated value of $(n_i)_{av}$ implies that the average electron density will start at $\sim 10^{21}$, and then approach several times 10^{21} as heating by the main pulse causes additional ionization. Although the laser light is absorbed in the underdense region, higher electron densities are achieved by conduction past the critical

density point. Finally, the calculated slope and plasma thickness are essentially the same as in the computer calculations presented in Section V and designated by "Plasma Profile A." This is all in accordance with the macroscopic design principles discussed in Section II.

With regard to the calculations for the main pulse, the first computer run in Section V predicts that most of the X-rays are emitted in the form of spectral lines, and that the conversion efficiency of laser light into X-rays is at least 20 percent. This computation uses plasma profile A and an incident power density of 10^{14} watts/cm^2, chosen to correspond to the foot and main pulse of the principle experiments. The prediction that reradiation is predominantly spectral lines is attributed to the time dependent model for ionization. In this model the average degree of ionization, and hence the average energy $h\nu = \chi_r$ of the available line transitions, substantially lags the electron temperature kT_e during the heating process. The average value of χ_r/kT_e is therefore much lower than the one predicted by the Saha Equation. This raises the power of line radiation, but lowers its average frequency. The second computer run presented in Section V is a "control" run which is performed with the same input conditions as the first, except for the unphysical assumption that the ion populations are predicted by the Saha Equations. Calculations of X-ray conversion efficiencies based on this type of model have recently appeared elsewhere, but these results can be highly misleading, as seen from FIGS. 18–23 and Table 4. In spite of the fact that relatively high conversion efficiencies are predicted, most of the radiation is erroneously calculated to be free-bound radiation, and furthermore, the average photon energy is too high by a factor of 10. It is noteworthy that all of the computer runs, except the unphysical ones designated "Equilibrium Calculation," predict that most of the radiation is in the form of spectral lines. It should be mentioned that this point that in the bent crystal spectrometer measurements made with the Lockheed Group, the radiation appears to be mostly lines in the spectral interval studied (~0.7 to 1.3 keV). A typical spectrum is shown in FIG. 29, which was taken at a crystal angle of 20° and a viewing angle normal to the target.

The high conversion efficiencies predicted in the computer calculations at 10^{14} watts/cm^2 were largely due to energy conducted past the critical density point. The underdense region becomes heated to several kilovolts, but the bulk of the radiation is produced by spectral lines emanating from the relatively cool (≤ 1 keV) leading edge of the thermal diffusion front. It is gratifying that this description was supported by the experiments. The high energy X-rays emitted from the hot, less dense, outer region of the plasma were observed through thick layers of absorber. This high temperature component is consistent with a conversion of ~1 percent of the incident laser energy to free-free and free-bound radiation with an electron temperature of ~5 keV. It is unnecessary to invoke plasma instabilities to account for it. The cold regime was analyzed by transmission measurements through thin foils of carbon and beryllium. A typical spectral envelope of this regime, which was obtained by unfolding the beryllium transmission curve (FIG. 26), is shown in FIG. 27. A key feature of this spectrum is the sharp increase in X-ray intensity as the frequency decreases to the regime where L-lines are predicted. The slope of the upper part of the curve indicates an electron temperature of less than 1 keV in the region where the lines are predicted.

Another significant feature of the experiments is the change in reflection which occurred when the foot was varied. FIG. 30 shows that most of the light is reflected for feet which are 1 to 2 nanoseconds long, and that the reflection drops to less than 50 percent for foot lengths much greater than 10 nanoseconds. The decrease in reflectivity was accompanied by an increase in the observed temperature. Now it is tempting to attribute the temperature increase to the simple fact that a decrease in reflectivity implies a greater power delivered to the plasma. This is undoubtedly part of the explanation, but the computer calculations refute this as the major cause. The computer runs were performed with initial conditions corresponding to a large range of foot lengths, and predict the same reflection and temperature trends as were observed. But they also imply the existence of a critically short foot. The plasma in that case behaves much like the foot plasma described in the Appendix (essentially blackbody). It now becomes clear how the often invoked blackbody temperature limitation for laser generated plasmas (~180 eV at 10^{14} watts/cm^2) is circumvented by a sufficiently long foot. This explanation is also valuable in interpreting the decrease in temperature with atomic number shown in FIG. 31, where all of the shots were made with a foot which gave good conversion efficiencies for iron. Scaling considerations based on the FLASH formulas and the foot formulas given in the Appendix predict that a foot which leads to a 20 percent conversion efficiency for iron will approach a blackbody response for the main pulse at higher-Z. This insight provides a clue for obtaining high conversion efficiencies above 1 keV with the heavier elements. A satisfactory procedure might be to use a longer and less powerful foot. The end result would probably be a higher energy spectrum than obtained from iron, but with comparable conversion efficiencies.

We now turn to the question of optical thickness. The FLASH radiation model assumes that the plasma is optically thin to its own radiation. Transmission measurements through 1 mil of beryllium show that the X-rays above ~1 keV are most intense in the direction normal to the target (90°), and drop off by up to a factor of two in intensity at 0°. This demonstrates the existence of a noticeable but not troublesome self absorption effect above ~1 keV. The plasma probably cannot be considered optically thin much below 1 keV, so that the model should probably be modified there to include self absorption.

The key test of the overall understanding is to verify the high conversion efficiencies which are predicted. This has been done in several ways. One method was the material damage threshold calorimeter technique illustrated in FIG. 28, which established lower bounds for the X-ray yield and provided a permanent record of the X-ray damage. In a typical verification shot for conversion efficiency, a 22 joule laser pulse struck an iron slab in the usual experimental configuration (FIG. 1). A material damage threshold calorimeter with a 1 mil beryllium foil and a 2000 A lead film was placed 0.43 cm from the plasma at a viewing angle of 0°. The lead was vaporized down to the substrate. Since the density and total energy of vaporization of lead are 11 gm/cm^3 and 1200 joules/gm, the X-ray fluence absorbed by the lead at that point was 0.26 joules/cm^2.

Now the lead absorbs only a minor fraction of the incident fluence. The rest is stopped by the beryllium or passes through both the beryllium and the lead. A plot of the fraction absorbed in lead versus photon energy is

given in FIG. 33, and shows that any spectrum of X-rays in the several keV range or lower will at most be 20.2 percent absorbed in the lead. The lower bound fluence emitted at 0° is thus 0.26/0.202 = 1.29 joules/cm². Since 0° is the angle of minimum flux, a lower bound estimate for the X-ray fluence emitted into the experimentally observable 2π steradian solid angle is $2\pi \times (0.43)^2 \times 1.29 = 1.50$ joules, which corresponds to a conversion efficiency of 6.8 percent. The sharp dropoff of the curve in FIG. 33 near 1 keV implies that most of the 6.8 percent is above 1 keV. The appropriate number to compare with theory is the lower bound conversion efficiency of 13.6 percent for X-rays emitted in 4π.*

Another calorimetric measurement used 0.1 mil nickel resistance thermometer elements behind 1 mil of Be or 3000 A of parylene coated with 2000 A of Al. The angular distribution of the X-rays is shown in FIG. 32. The conversion efficiency based on transmission through the thin parylene is about 25 percent over 2π steradians. The average transmission through 1 mil of Be is about a factor of 5 lower.

VIII. CONCLUSIONS

The main conclusions drawn from this study are the following.

I. Conversion efficiencies of 6–10 percent into 2π over ~1 keV have been demonstrated with nanosecond laser pulses on slabs. Slabs of proper thickness will permit use of the full 4π.

II. Slab targets have several advantages for large laser systems. Focusing is simplified, the output is reproducible, and the initial plasma profile is conveniently established with a foot. Amplified spontaneous emission does not disrupt the target. Large outputs can be obtained in a desired pulse shape with a multiple pulse technique, with the pulses sequentially targeted at separate points on the slab.

III. An understanding of the basic phenomenology is essential for optimizing the output. The bulk of the X-rays are produced by spectral lines emanating from the relatively cool ($\leq$ 1 kev) leading edge of a thermal diffusion front. A hard component is emitted from a hot low density region with ~1 percent conversion efficiency, and corresponds to free-free plus free-bound radiation at ~5 keV electron temperature. The spectrum and conversion efficiencies are strongly modified by the lag in ionization due to nonequilibrium stripping. Nonequilibrium stripping raises the output, lowers free-bound output, and lowers average photon energy. Conversion efficiencies are generally higher than with the Saha Equilibrium ionization model. Strong laser absorption can be predicted without invoking instabilities. The output can be varied by tuning the initial plasma conditions with a foot. Higher-Z elements promise to yield higher average photon energies.

IV. A diminished debris problem due to high conversion efficiency has been demonstrated. Over 1 joule/cm² of soft X-rays were delivered over a usable area, free of debris.

V. The laser must be protected from glass damage caused by light backscattered from targets. An isolation technique has been developed which is applicable to lasers of any aperture.

VI. The nanosecond output of the final stage of the VD-640 can be increased by a factor of five without glass damage. The single pulse output was increased from 100 to 240 joules, and 350 joules were produced in a double pulse mode. At least 500 joules is available in the double pulse mode without serious modification.

Further development promises to provide a unique soft X-ray for medical applications such as cancer therapy, and may also ultimately lead to a brute force X-ray laser. An X-ray laser which produces a joule or so of coherent X-rays would greatly aid the life sciences by providing phase information in X-ray diffraction studies of genetic materials. The interaction of a laser with high-Z matter is also useful for controlled thermonuclear fusion. Although most of the emphasis in laser generated fusion to date has been on low-Z materials, use of a high-Z material in conjunction with deuterium and tritium may lower the threshold laser energies required for controlled thermonuclear fusion.

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United States Patent [19]

Elton

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[54] RESONANT PHOTON PUMPING MECHANISMS FOR A PLASMA X-RAY LASER

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[73] Assignee: The United States of America as represented by the Secretary of the Navy, Washington, D.C.

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[22] Filed: Jan. 10, 1984

[51] Int. Cl.[4] H01S 3/30

[52] U.S. Cl. 372/5; 372/69; 372/68

[58] Field of Search 372/3, 5, 69, 70

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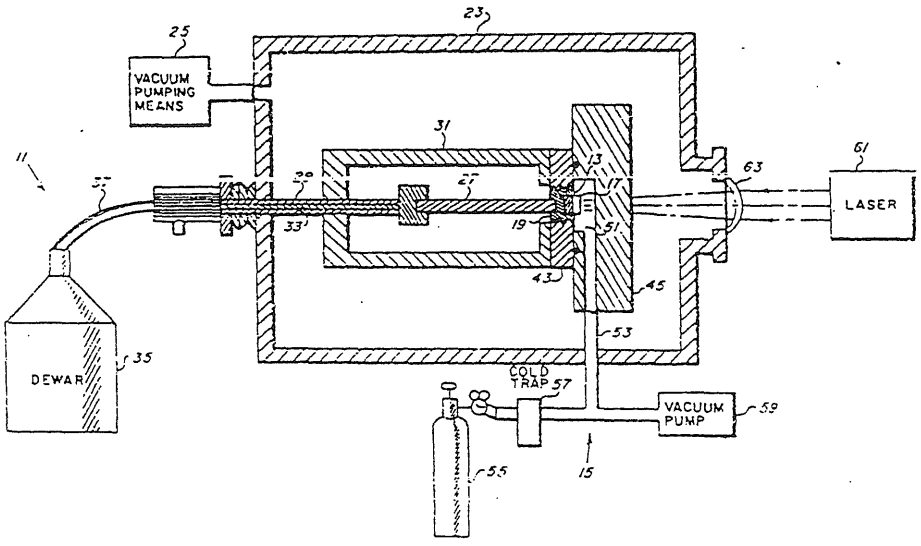
Primary Examiner—Léon Scott, Jr.

Attorney, Agent, or Firm—Robert F. Beers; Sol Sheinbein; William T. Ellis

[57] ABSTRACT

A lasing system for lasing at x-ray wavelengths. In one embodiment, a neon-like sulfur ion S^{6+} plasma is caused to radiate on its 3d→2p transition to pump a lithium-like neon Ne^{7+} plasma to obtain x-ray lasing. In a second embodiment, a lithium-like silicon Si^{11+} ion plasma is caused to radiate on the 3d→2p transition to pump lithium-like magnesium Mg^{9+} plasma to obtain x-ray lasing.

11 Claims, 4 Drawing Figures



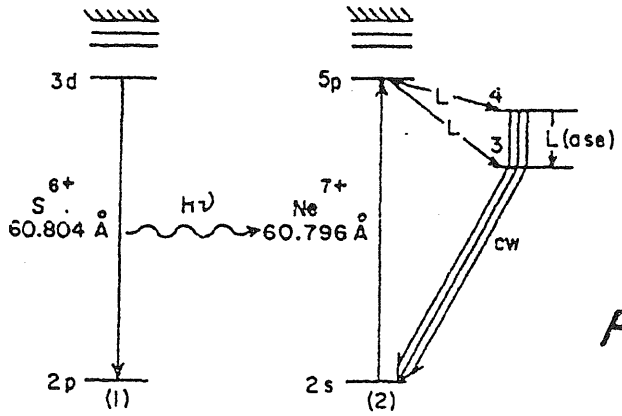


FIG. 1

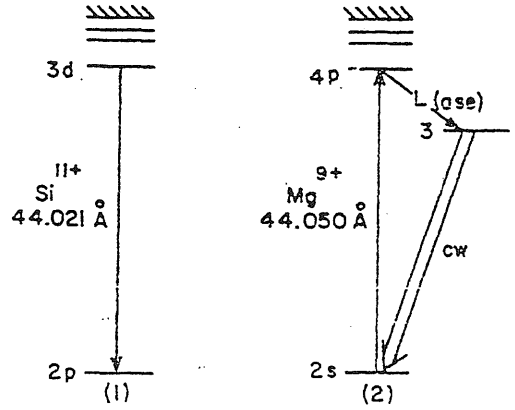


FIG. 2

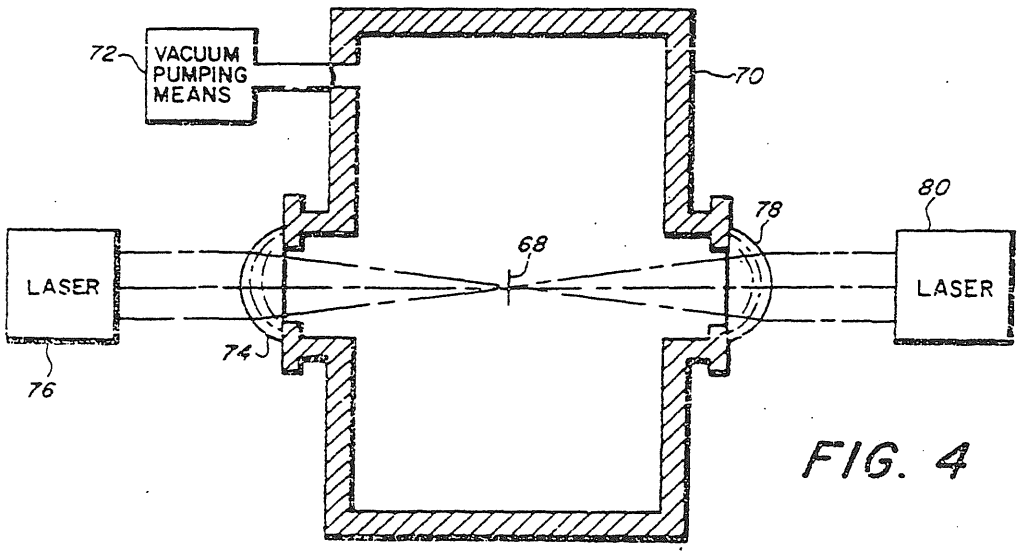


FIG. 4

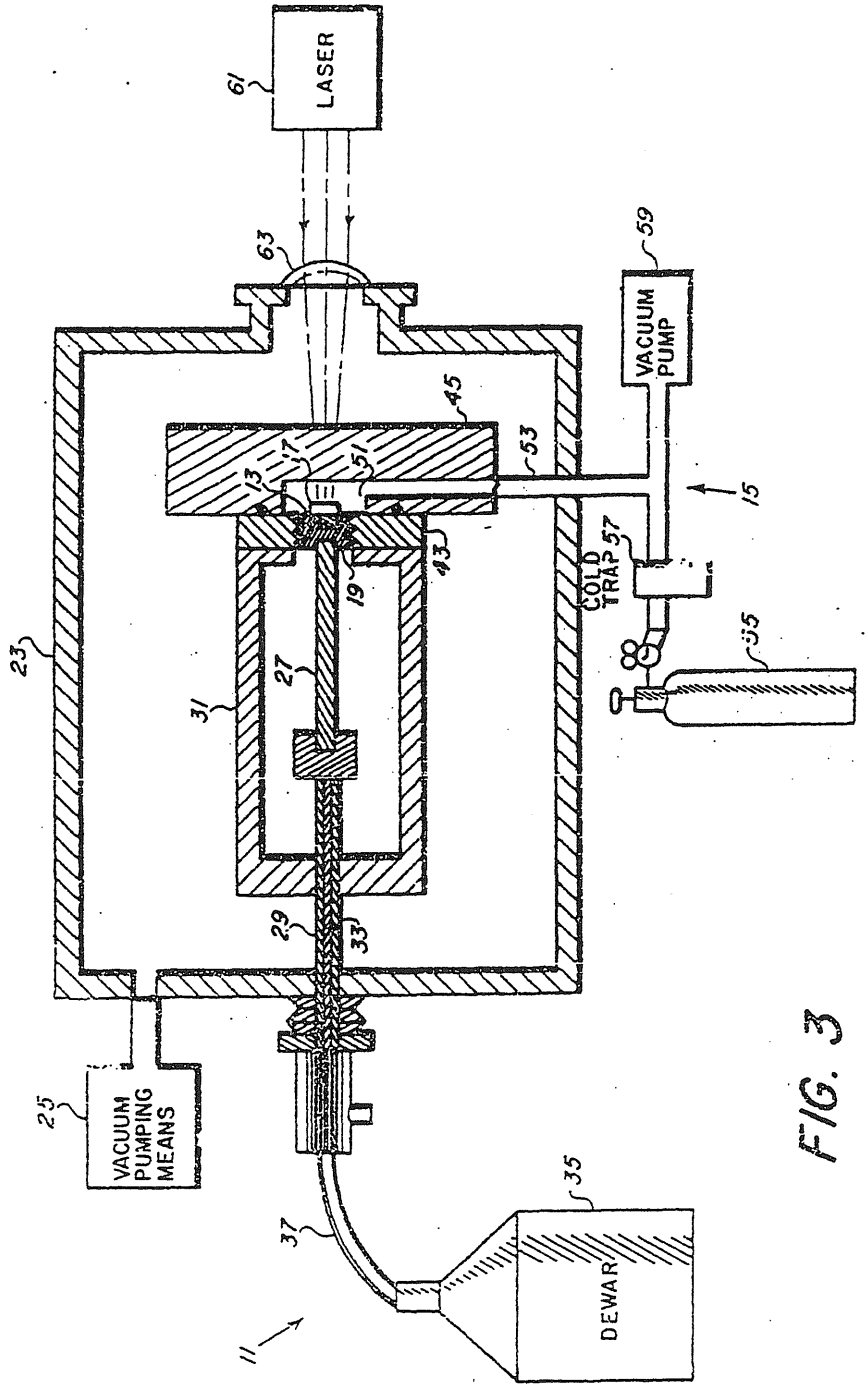

LASER
61
63
59
VACUUM PUMP
45
53
51
13
17
15
43
19
COLD TRAP
57
55
23
27
31
29
33
25
VACUUM PUMPING MEANS
35
37
DEWAR
11

FIG. 3

RESONANT PHOTON PUMPING MECHANISMS FOR A PLASMA X-RAY LASER

BACKGROUND OF THE INVENTION

The present invention relates generally to lasers and laser pumping systems, and more particularly to mechanisms for photon pumping a population inversion on selective energy levels in highly stripped plasma ions in order to obtain lasing at x-ray wavelengths.

There is strong interest in achieving laser action in the x-ray range ($1Å < \lambda < 700Å$) and many novel schemes have been proposed. The potential applications for a coherent source in the x-ray wavelength regime include bio-medical research and holography wherein the x-ray laser radiation would be utilized to "photograph" objects with dimensions below 1,000 Angstroms. Such an x-ray laser would also be useful in the study of high density plasmas for laser fusion. Remote sensing of various elements using x-ray induced fluorescence or diffraction is another potential application.

The achievement of significant gain in the spectral region located at wavelengths shorter than 1000 Angstroms, where reflecting cavities become very inefficient, requires very high inverson population densities in the upper energy state that is to lase as well as high pump power densities. Additionally, it is required to create population inversions on high energy transitions in order to obtain gain at short x-ray wavelengths. The pump power density required in order to obtain this population inversion generates highly-stripped ions in a high temperature plasma state of matter. A highly stripped ion is an ion with many electrons removed, typically through collisions with other particles via heating at temperatures on the order of one million degrees Kelvin (100 eV). In the prior art, pumping has been attempted via electron and ion collisions as well as by photoionization. By way of example, Pat. No. 4,229,708 to Mani et al. discloses an x-ray laser wherein a metastable state is pumped via photoionization.

A highly efficient method of pumping to obtain coherent x-ray radiation uses an intense spectral line from one plasma ion to pump on an absorption transition in another plasma ion, with nearly the same nuclear charge, and as nearly an exact wavelength match between the two transitions as possible. Note that the ions in the two different plasmas should have approximately the same nuclear charge in order to ensure that they will coexist together in close proximity at the same temperature. The particular degree of ionization ion present (the number of electrons stripped from the particular atom) will depend very strongly on the temperature at that particular location. Thus, it is essential that the desired pumping ion and lasing ion coexist at a particular temperature.

Wavelength coincidences within the natural or Doppler linewidths are rare. (Note that Doppler linewidths, i.e., the spectral broadening due to the movement of ions in the plasma causing changes in the frequency of the radiation detected, are usually on the order of a few tens of milli-Angstroms.) Two promising possibilities for such wavelength coincidences involve hydrogenic potassium pumping hydrogenic chlorine, and helium-like sodium pumping helium-like neon. These ions in the $Z = 10–20$ range with only one or two electrons remaining require very high temperatures usually created only in a point or short line focus of a high power state-of-the-art pump laser. The high power lasers required for this type of pumping are expensive.

It can be seen that there is an urgent need for alternate combinations of pump and laser ions that function at lower temperatures, and can be routinely studied with moderate power laboratory lasers. Such alternate combinations should be adaptable to extension to centimeters of length in line focus via cylindrical and spherical lens combinations in order to permit high gain experiments on large pump facilties.

OBJECTS OF THE INVENTION

Accordingly, it is an object of the present invention to provide combinations of pump and laser ions which will function at lower plasma temperatures.

It is a further object of the present invention to generate lasing at short x-ray wavelengths using highly-stripped ions in relatively low temperatures plasmas.

SUMMARY OF THE INVENTION

Briefly, the above and other objects are achieved in one embodiment by means of a lasing producing system which includes apparatus for generating a pumping plasma of neon-like sulfur ions S^{6+} which radiate on the $3d \rightarrow 2p$ transition, and further includes apparatus for generating a plasma of lithium-like neon ions Ne^{7+} which absorb on the $2s \rightarrow 5p$ transition, where the neon ion plasma is generated in close proximity to the sulfur ion plasma in order to obtain pumping radiation from the sulfur ion plasma and to provide quasi-cw lasing at X-ray wavelengths.

In one implementation of this embodiment, a laser may be disposed to focus a beam on a portion of solid sulfur with neon either frozen on the surface thereof, frozen nearby, or disposed thereover in the form of a high pressure gas.

In a second embodiment of the present invention, apparatus may be provided for generating a plasma of lithium-like silicon ions Si^{11+} which radiate on the $3d \rightarrow 2p$ transition, and apparatus for generating a plasma of lithium-like magnesium ions Mg^{9+} which absorb on a $2s \rightarrow 4p$ transition, wherein the magnesium ion plasma is generated in very close proximity to the silicon ion plasma in order to obtain pumping radiation therefrom and to provide quasi-cw lasing at x-ray wavelengths from the Mg^{9+} ions.

Note that both of the described embodiments permit x-ray lasing at lower plasma temperatures than the prior art and therefore can be made to operate at the focus of a modest laboratory laser.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an energy level diagram for the pumping-lasing plasma system of a first embodiment of the present invention.

FIG. 2 is an energy level diagram for the pumping-lasing plasma system of a second embodiment of the present invention.

FIG. 3 is a schematic diagram of an apparatus which may be utilized to pump lithium-like neon ions with neon-like sulphur ions.

FIG. 4 is a schematic diagram of an apparatus which may be utilized to pump lithium-like magnesium ions with lithium-like silicon ions.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

As noted above, in order to pump an x-ray transition directly, large photon energies are required. A standard laser beam, for example from an Nd^{+3} laser, does not provide sufficient photon energies to pump such x-ray transitions. In the present invention, such a laser beam pulse is used instead to vaporize and heat a pump material to generate plasma x-rays, which in turn, fall onto a nearby lasing material and pump the upper energy levels of that lasing material to inverted populations.

In essence, the present invention is a lasing system which utilizes matched-line photo excitation pumping. In this mode of pumping, specific ionic excited states are efficiently pumped to over-population relative to a lower state by narrow band near-resonance absorption of fine radiation. Note that while it is possible to consider pumping by the same ion and transition as is used for the absorber/lasant ion, usually this emission is insufficient for lasing purposes. Hence, ions of different species are generally required.

When a population inversion is created, stimulated emission competes with flourescent emission. Optimum pumping is obtained with the emission and absorption transitions at precisely the same energy and bandwidth (i.e., wavelength and linewidth).

Accordingly, it can be seen that matches must be found between the emission and absorption transitions of the various ionic species. Moreover, certain additional criteria must be invoked for the pumping-laser system candidates. Besides the overlap of ion transition widths, strong transitions are required for the pump ion in order to assure emission saturation, and a strong absorber ion transition is required for efficient pumping in order to ensure high gain for a given laser line. Rapid lower-laser-state population depletion is also desirable for quasi-cw operation. Moreover, the achievement of lasing between low-lying energy levels of the lasant may avoid photoionization by the laser beam. In addition to these "atomic considerations", it is also desirable to have pumping and lasing plasmas of comparable charge and temperatures to maintain a large solid angle of photo coupling and congruent ionic species.

It has been discovered that a neon-like (stripped to 10 electrons like neon) sulfur ion designated S^{+6} radiates on a 3d→2p transition at 60.804 Angstroms and can be used to pump a lithium-like (stripped to 3 electrons like lithium) neon ion designated Ne^{+7} on a 2s→5p absorption transition at 60.796 Angstroms, with a wavelength difference of only 8 milli Angstroms. Note that the 3d→2p transition is a closed shell pumping transition. This S^{+6}—Ne^{+7} lasing combination meets all of the above requirements. Note in particular that the wavelength difference between the sulfur ion emission and the neon ion absorption of 8 milli-Angstroms is comparable to the milli-Angstrom Doppler linewidth in a T = 100 eV plasma in which these ions could be created. In this regard, the S^{+6} ionizes at 281 eV and the Ne^{+7} ionizes at 239 eV energies.

The 3d→2p pumping transition for the sulfur ion and the 2s→5p absorption transition of the neon ion are shown in FIG. 1. It can be seen that quasi-cw amplification takes place on the 5→4, 4→3 and the 5→3 transitions in the Ne^{+7} at 564, 221 and 183 Angstroms, respectively. Note that all three of these lasing transitions have a rapid lower laser state depletion to prevent bottlenecking.

Both the pumping and lasant plasmas may be created at the focus of a single high power laser, or by using two high power lasers focusing on points in close adjacency. The sulfur may be conveniently in slab form and the neon may be either frozen onto the surface of the sulphur slab or onto a material adjacent to the sulfur, or generated in a gas adjacent to a surface of the sulfur slab. There are a variety of high power lasers which may be utilized to implement the present invention. By way of example, and not by way of limitation, an Nd: glass "visible" laser may be utilized. In the experiments performed with this combination of pump and lasant material, a 10600 Angstroms Nd-glass driving laser was operated at 20J, 10 ns, and focused to a 0.5 mm diameter spot on a sulphur slab target. This results in approximately 10^{12}watts/cm^2 of power applied to the sulfur slab target.

An apparatus for cryogenically fabricating a sulfur slab with neon frozen on a portion of the surface is disclosed in U.S. Pat. application Ser. No. 500,725, filed June, 3, 1983, by R. C. Elton, R. H. Dixon, and J. L. Ford. This patent application is hereby incorporated by reference into the present disclosure.

FIG. 3 of the present disclosure sets forth the apparatus disclosed in that '757 patent application for freezing the neon onto the surface of the sulfur. This apparatus includes a cooling circuit 11 which is employed to cool a sulfur substrate 13 in order to hold the normally-solid sulfur material below the freezing point of neon gas. The apparatus also includes a supply means 15 employed to supply the gaseous atmosphere of neon to the cooled sulfur substrate 13 so that a frozen layer 17 condenses onto the substrate to form the target.

In the example apparatus shown in FIG. 3, the cooling means 11 takes the form of a thermally-conducting block 19 having a top face that includes a recess for mounting the substrate 13 of the sulphur material, and a cryostat comprising a housing 23 surrounding the block 19, a vacuum pumping means 25 communicating with the housing 23, a thermally conducting rod 27 disposed inside the housing and connected to the bottom face of the block 19, a cold finger 29 passing through the housing by way of a vacuum seal and connected to the rod 27, and a radiation shield 31 connected to the cold-finger and surrounding the rod 27 and part of the cold-finger 29. The cold-finger 29 has a central channel 33 adapted to receive a coolant such as liquid helium from a dewar 35 disposed outside the housing 23 via a transfer line 37.

The supply means 15 is shown in FIG. 3 to include a thermally insulating jacket 43 of lucite sealingly enclosing the side wall of the block 19 and fitted against the radiation shield 31. A removable thermally-insulating cap 45 sealingly engages the top face of the jacket 43. The cap 45 has a hole 51 adapted to coincide with the mounted substrate 13 and to communicate by way of a bifurcated tube 53 with an external pressurized source 55 of gaseous neon preceded by a cold trap 57 of liquid nitrogen and a vacuum pump 59.

In operation, the sulfur substrate 13 is mounted in the recess in the top face of the block 19 and then the cap 45 is sealingly engaged to the jacket 43. The block 19 is then cooled and maintained of 8° Kelvin absolute for neon by evacuating the housing 23 with the vacuum pump 25 and transmitting liquid helium from the dewar 35 by way of the transfer line 37 and connector 39 through the channel 33. Next, the neon gas is supplied to the mounted substrate 13 through the hole 51 in the

cap 45 from the pressurized source 55 and the cold trap 57 that pre-cools the gas. The pressure of the gas may be 1.5 atmospheres for neon. A pool of neon gas liquifies on the substrate 13 and then forms a frozen layer on the substrate. The remaining gas is then pumped from the hole 51. In order to expose the sulfur target, the cap 45 is removed. An external Nd glass laser may then be focused on the target by means of a lens 63 disposed in the wall of the housing 23 opposite the target.

It should be noted that for maximum gain, a lasant plasma with cool ions should be essentially congruent with the hot dense pumping plasma. This may be accomplished by maintaining a portion of the surface of the sulfur substrate 13 free of the frozen neon, possibly by covering it with a portion of the cap 45. Then a second laser may be focused on this uncoated portion of the sulfur substrate adjacent to the neon-coated portion. These two lasers (only one laser is shown in FIG. 3) would both be focused through lens 63 and would be slightly offset. This two laser configuration allows the neon to expand a little further away from the sulfur material that it is pumping. The separation between the uncoated portion of the substrate 13 and the neon coated portion may on the order of 100 μm. A first laser pulse would be applied to the bare sulfur portion of the substrate, and then a second laser pulse would be applied to the neon coated portion of the substrate 13 approximately 1 nanosecond later. It should be noted, that this separation of the pumping and lasant plasmas is not essential, but is considered to optimize the resulting gain.

In another implementation, a neon gas could simply be disposed adjacent to a surface of a sulfur slab target. Only approximately one-tenth of an atmosphere of neon gas would be required. When a laser is focused on the sulfur slab target, the electrons in the sulfur ion plasma generated act to break down or ionize the surrounding neon gas thereby permitting lasing.

It should be noted that the present sulfur-neon ion lasing system requires a lower plasma temperature because the ions are not one or two electron ions which required higher temperatures to generate, but rather lithium-like and neon-like ions containing three electrons and ten electrons, respectively. This design feature permits a much smaller laser to be used.

In a second embodiment of the present invention, lithium-like silicon Si^{+11} with a transition of 3d→2p is used to pump lithium-like magnesium Mg^{+9} which absorbs on the 2s→4p transition. The emission wavelength for the lithium-like silicon ion is 44.021 Angstroms and the absorption wavelength for lithium-magnesium ion is 44.050 Angstroms, with a difference therebetween of 30 milli-Angstroms. This silicon ion emission and magnesium ion absorption match is shown in FIG. 2. Note that the ionization potentials for this embodiment are 523 eV for silicon and 367 eV for magnesium. Thus, slightly higher temperatures in the range of 150 eV are required in the plasmas. The lasing occurs on the 4→3 transition for the magnesium ion at 170 Angstroms.

Note that the Doppler linewidths are about 8 milli-Angstroms, which is approximately only ¼ of the wavelength difference between the silicon ion pump emission wavelength and the magnesium ion absorber wavelength. Accordingly, additional Stark broadening at higher electron densitites (approximately 10^{21} cm^{-3}) or Doppler shifting with relative streaming is required. In this disclosure, Stark broadening is defined as the collisional broadening which is obtained when the electric field from one ion causes other ions to change their radiating frequency slightly. In this context, the term Doppler shifting with relative streaming means the Doppler shift obtained when ions are streaming away from other ions. It should be noted that there are a number of techniques to obtain this spectral broadening in order to make up the 30 milli-Angstrom difference between the emission and the absorber wavelengths. By way of example, a thin foil made by evaporating or sputtering silicon onto one or both sides of a magnesium foil may be used as the target for the device. This foil may then be hit from opposite sides with two different lasers. As the foil is hit from oppposite directions by the lasers, the plasmas formed thereby expand back toward those laser beams thereby causing the ions in those plasmas to move away from each other. The resulting Doppler shift is sufficient to permit the pump emission to be absorbed by the lasant ion.

FIG. 4 shows one embodiment of an apparatus which may be utilized to hit a thin foil from opposite directions with two different laser beams. In this configuration, a thin foil 68 is disposed in a vacuum chamber 70. The vacuum chamber 70 includes a vacuum pumping means 72 for providing the proper vacuum pressure. For the silicon ion-magnesium ion lasing system, the pressure may be 10^{-3} Torr. A first focusing lens 74 is utilized to focus a beam from a laser 76 through an opening in the vacuum chamber 70 on to one side of a thin foil target 68. A second focusing lens 78 is utilized to focus a beam from a second laser 80 through a second opening in the vacuum chamber 70 to impinge on the thin foil 68 from the opposite direction from the first laser 76. Note again that the lasers 76 and 80 may be realized by a 10000 Angstrom Nd-glass driving laser operated at 20 J, 10 ns, and focused to a 0.5 mm diameter spot. The approximate amount of power required by the laser on the spot is 10^{13} Watts/cm^2. The temperature in the vacuum chamber 70 may be room temperature.

It should be noted that both of the lasing systems disclosed in the present invention permit significantly lower plasma temperatures than the prior art. Therefore, these systems can be made to operate at the point focus of a modest laboratory laser or over an extended length for maximum gain with increased but still moderate pump power.

It should also be noted that the embodiments of the present invention utilize lithium-like and neon-like ions which are plentiful in a pulsed plasma. Also, the 3d→2p pumping transition for the pump ions are known to produce some of the most intense spectral lines available in pulsed laser plasmas. The embodiment utilizing the neon-like sulfur ion pumping the lithium-like neon ion has a wavelength decrement within the width of the spectral lines involved. The embodiment utilizing the lithium like silicon ions pumping the lithium-like magnesium ions features metallic materials readily available in solid form for convenient target configuration.

The lasing systems of the present invention avoid the use of photoionization schemes and the need for pumping intermediate metastable states. More specifically, the present invention involves the photoexcitation to a specific lasing energy level by a matching emission line, i.e, a tuned photon source. The present process is a one-step process since direct resonant pumping of a particular laser level is utilized.

It should be noted that the present lasing systems are cw in operation and the population inversions generated

by the pumping ions for these systems persist for many passes through a resonant cavity. This feature is in contradistinction to many prior art X-ray systems which self-terminate rapidly on a ground state. It should also be noted that many prior art lasing systems deplete the population inversions in their metastable and upper laser states due to ionization caused by their lasing photons. This depletion creates excess ionized ground states so that any lasing quickly quenches itself. However, the present lasing system obtains an x-ray output photon energy which is lower than the photoionization threshold for the levels involved, thereby obviating this problem.

Obviously many modifications and variations of the present invention are possible in light of the above teachings. It is therefore to be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

What is claimed and desired to be secured by Letters Patent of the United States is:

1. An amplified spontaneous emission x-ray laser comprising:

means for generating a plasma of neon-like sulfur ions S^{6+} which radiate on a 3d-2p transition; and

means for generating a plasma of lithium-like neon ions Ne^{7+} which absorb on a 2s-5p absorption transition, said neon ion plasma being generated in close proximity to said sulfur ion plasma in order to obtain pumping radiation from said sulfur ion plasma, wherein said neon-like sulfur ion 3d-2p transition is resonant with said lithium-like neon ion 2s-5p absorption transition to create a population inversion in said plasma of neon ions to provide quasi-cw lasing of said neon ion plasma at x-ray wavelengths between 1A and 700A by amplified spontaneous emission.

2. An x-ray laser as defined in claim 1, wherein said generating means comprise a solid sulfur target with neon frozen on a first surface thereof; and

and a laser disposed to focus a laser beam on a portion of the first surface of said solid sulfur target.

3. An x-ray laser as defined in claim 1, wherein said generating means comprise a solid sulfur target with neon disposed over a first surface thereof in the form of a gas; and

a laser disposed to focus a laser beam on a portion of the first surface of said solid sulfur target.

4. An x-ray laser as defined in claim 1, wherein said ion plasma generating means comprises:

a solid sulfur target with a first and a second adjacent small area, said second small area having a layer of neon disposed on the surface thereof;

a first laser;

a second laser; and

means for focusing light emitted from said first laser onto said first small area on said solid sulfur target, and for focusing light from said second laser onto said second small area on said sulfur target adjacent to said first small area.

5. A method for generating x-ray radiation comprising the steps of:

generating a plasma of neon-like sulfur ions S^{6+} which radiate on a 3d-2p transition; and

generating a plasma of lithium-like neon ions Ne^{7+} which absorb on a 2s-5p absorption transition, said neon ion plasma being generated in very close proximity to said sulfur ion plasma in order to obtain pumping radiation therefrom, wherein said neon-like sulfur ion 3d-2p transition is resonant with said lithium-like neon ion 2s-5p absorption transition to create a population inversion in said plasma of neon ions to provide quasi-cw lasing amplification at x-ray wavelengths between 1A and 700A from said Ne^{7+} ions by amplified spontaneous emission.

6. A method as defined in claim 5, wherein said plasma generating steps comprise the step of directing a laser to focus onto a portion of solid sulfur with neon frozen on the surface of the sulfur.

7. A method as defined in claim 5, wherein said plasma generating steps comprise the step of directing a laser to focus onto a portion of solid sulfur with neon disposed thereover in the form of a gas.

8. A method for generating x-ray radiation comprising the steps of:

generating with spectral broadening a plasma of lithium-like silicon ions Si^{11+} which radiate on the 3d-2p transition; and

generating with spectral broadening a plasma of lithium-like magnesium ions Mg^{9+} which absorb on a 2s-4p transition, said magnesium ion plasma being generated in very close proximity to said silicon ion plasma in order to obtain pumping radiation therefrom, wherein said lithium-like silicon ion 3d-2p transition resonant with said lithium-like magnesium ion 2s-4p transition to create a population inversion in said plasma of magnesium ions to provide quasi-cw lasing at x-ray wavelengths between 1A and 700A from said Mg^{9+} ions by amplified spontaneous emission.

9. A method as defined in claim 8, wherein said plasma generating steps comprise the step of directing two laser beams to focus on opposite surfaces of a thin foil target of magnesium with silicon sputtered thereon.

10. An x-ray laser comprising:

means for generating a spectrally broadened plasma of lithium-like silicon ions Si^{11+} which radiate on the 3d-2p transition; and

means for generating a spectrally broadened plasma of lithium-like magnesium ions Mg^{9+} which absorb on the 2s-4p transition, said magnesium ion plasma being generated in very close proximity to said silicon ion plasma in order to obtain pumping radiation therefrom, wherein said lithium-like silicon ions on the 3d-2p transition are resonant with said lithium-like magnesium ions on the 2s-4p transition to create a population inversion in said plasma of magnesium ions to provide quasi-cw lasing at x-ray wavelengths between 1A and 700A from said Mg^{9+} ions by amplified spontaneous emission.

11. An x-ray laser as defined in claim 10, wherein said generating means comprise

a thin foil target of magnesium with silicon sputtered thereon; and

apparatus for directing laser beams to focus on a point in said thin foil target from opposite directions in order to obtain plasma on each side of the target with a desired ion streaming.

* * * * *

United States Patent [19]

Cochran et al.

[11] **Patent Number: 4,803,687**

[45] **Date of Patent: Feb. 7, 1989**

[54] **THERMALLY BUFFERED SODIUM-NEON LASER TARGET FOR COHERENT X-RAY PRODUCTION**

[75] Inventors: **Frederick Cochran**, Alexandria; **Jack Davis**, Annandale; **John Apruzese**, Springfield, all of Va.

[73] Assignee: **The United States of America as represented by the Secretary of the Navy**, Washington, D.C.

[21] Appl. No.: 795,795

[22] Filed: Nov. 7, 1985

[51] Int. Cl.[4] H01S 3/30

[52] U.S. Cl. 372/5; 372/34

[58] Field of Search 372/5, 34, 39, 55, 68, 372/70; 378/119

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Primary Examiner—William L. Sikes

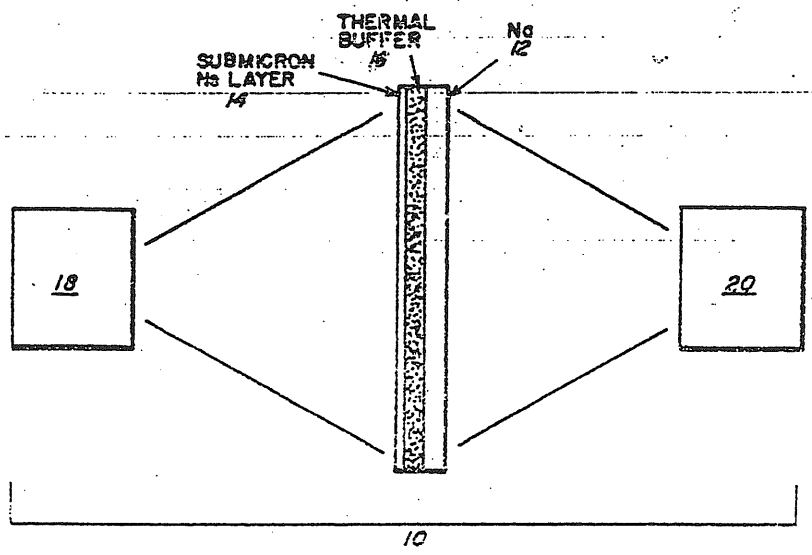
Assistant Examiner—B Randolph

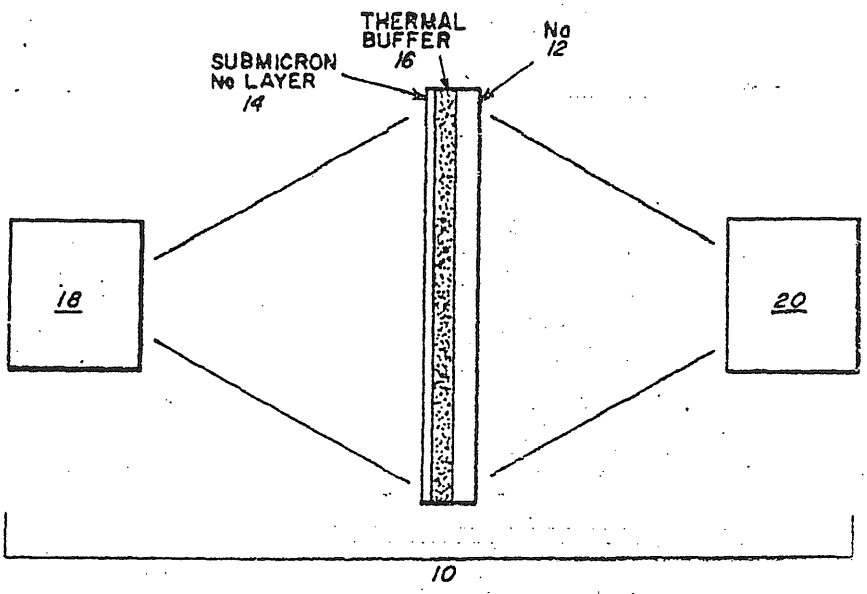
Attorney, Agent, or Firm—Thomas E. McDonnell; Peter T. Rutkowski

[57] ABSTRACT

A carbon layer between a neon layer and a sodium layer serves as a thermal buffer therebetween to enable the neon layer to remain at a lower temperature and density to allow for the generation of coherent x-rays. A high powered laser heats the sodium layer which acts as a flashlamp for direct photon pumping of the neon layer. The neon layer, heated by a lower powered laser, then lases at about 58, 82, and/or 230 angstroms.

6 Claims, 3 Drawing Sheets

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Na 12
SUBMICRON Na LAYER 14
18
20
10

FIG. 1

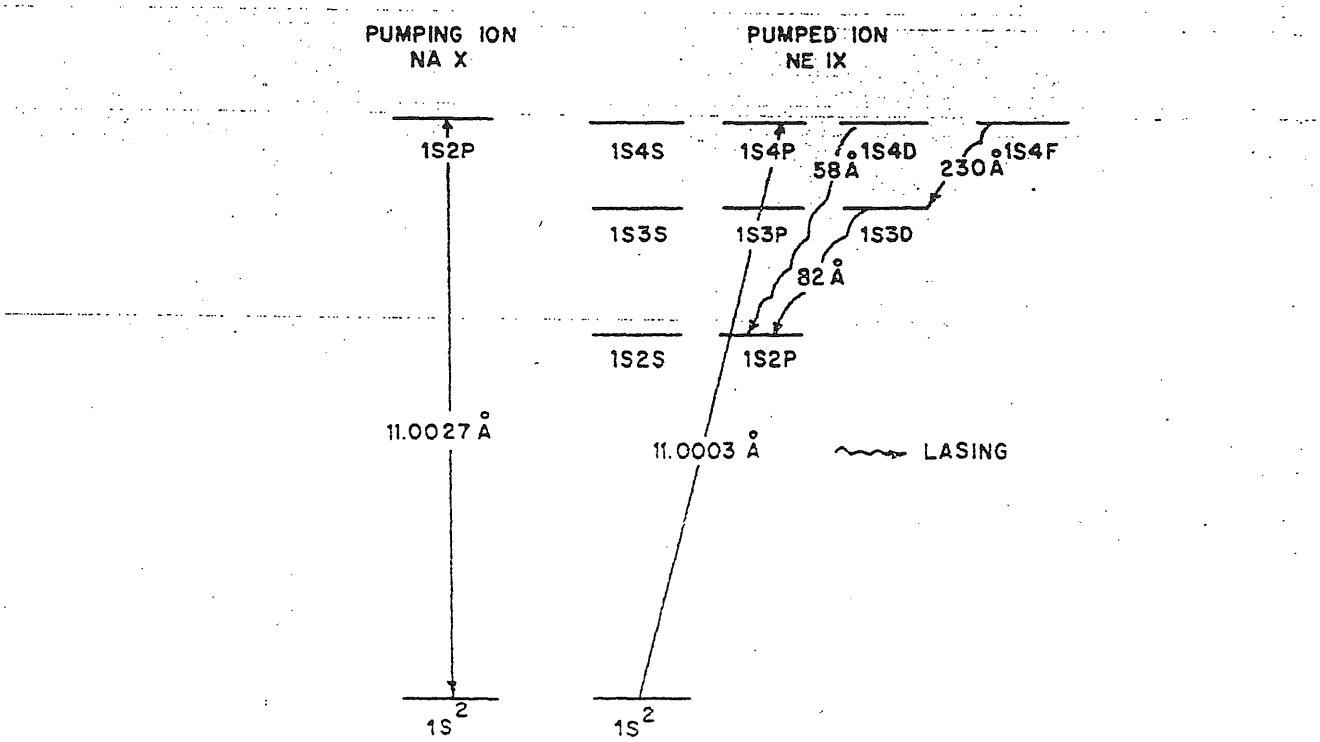
PUMPING ION NA X
PUMPED ION NE IX
1S2P
1S4S
1S4P
1S4D
1S4F
58 Å
230 Å
1S3S
1S3P
1S3D
82 Å
1S2S
1S2P
11.0027 Å
11.0003 Å
LASING
1S2
1S2

FIG. 2

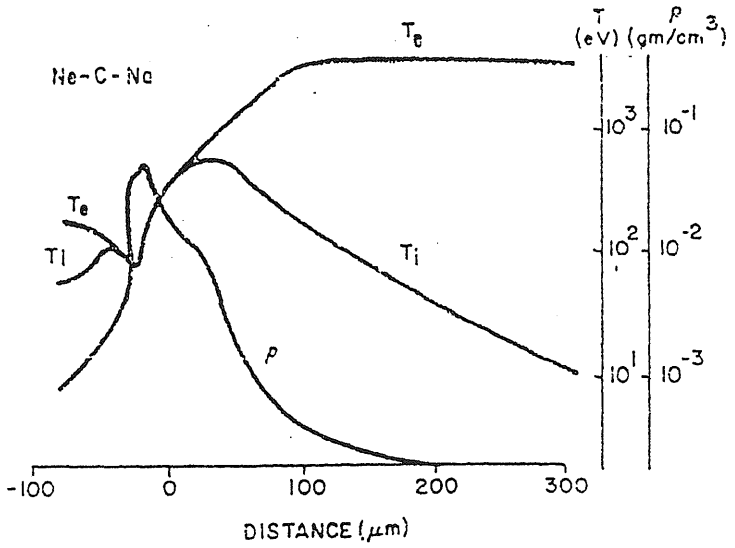
T
(eV)
ρ
(gm/cm³)
Ne-C-Ne
T_e
T_i
10^3
10^2
10^1
10^{-1}
10^{-2}
10^{-3}
-100
0
100
200
300
DISTANCE (μm)

FIG. 3

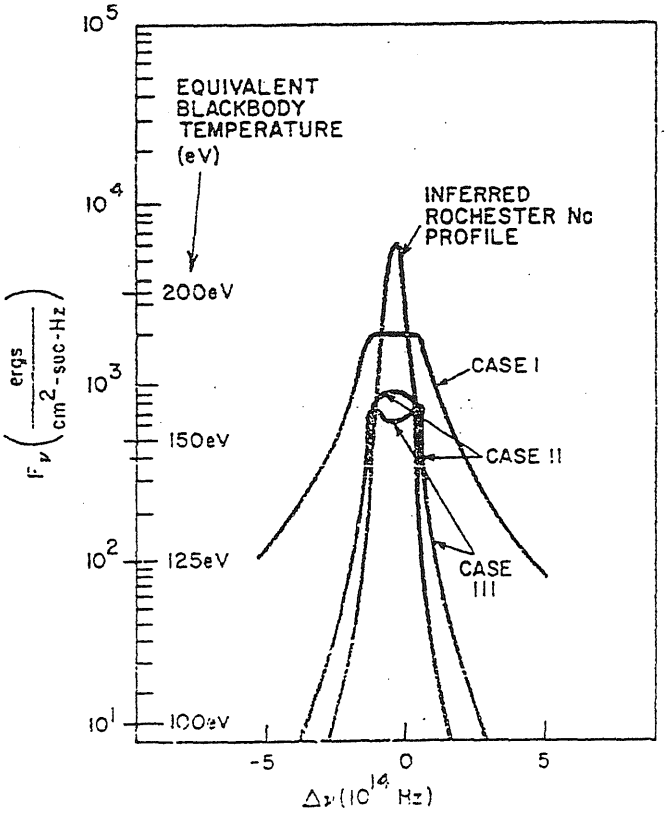
EQUIVALENT
BLACKBODY
TEMPERATURE
(eV)
200eV
150eV
125eV
100eV
INFERRED
ROCHESTER Nc
PROFILE
CASE I
CASE II
CASE
III
F_ν (ergs / cm²-sec-Hz)
10^5
10^4
10^3
10^2
10^1
-5
0
5
Δν (10¹⁴ Hz)

FIG. 5

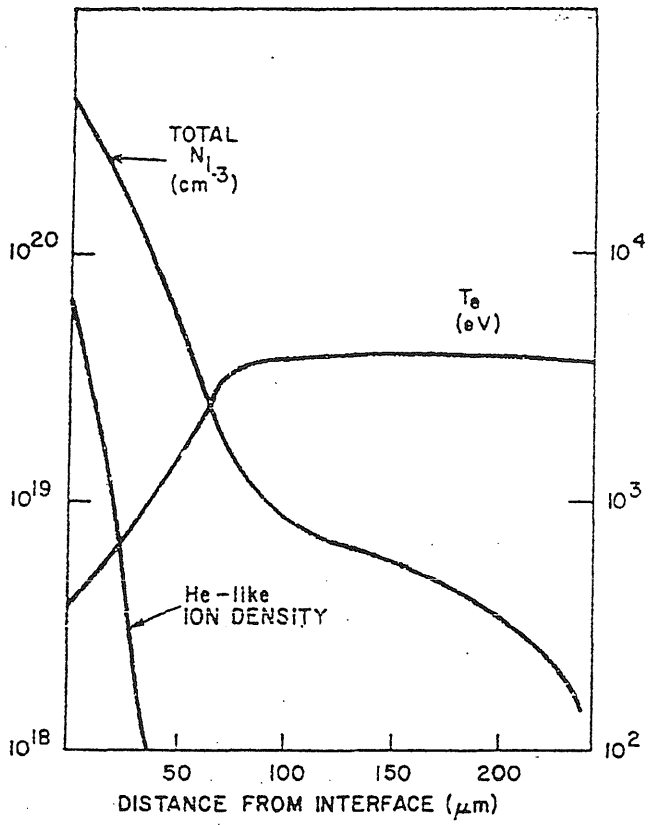
TOTAL
N_{I-3}
(cm^{-3})
10^{20}
10^{19}
10^{18}
10^4
10^3
10^2
T_e
(eV)
He-like
ION DENSITY
50
100
150
200
DISTANCE FROM INTERFACE (μm)

FIG. 4

THERMALLY BUFFERED SODIUM-NEON LASER TARGET FOR COHERENT X-RAY PRODUCTION

BACKGROUND OF THE INVENTION

The present invention relates to the generation of coherent x-rays. More specifically, the present invention relates to direct photon pumping in a Na-Ne system where a thermal buffer is inserted therebetween.

For many years now, there have been a variety of proposed schemes suggesting ways to create a population inversion and subsequent gain in the x-ray region. (A population inversion exists when the upper energy level in a transition is overpopulated relative to the lower energy level and is a necessary requirement for lasing to occur.) U.S. Pat. No. 4,206,364 to Dixon et al. describes a one sided laser irradiation scheme using tungsten blocks to create a channel for plasma from a carbon target. Population inversion occurs in the expanding carbon plasma. U.S. Pat. No. 4,229,708 to Mani et al. concerns producing lithium-like atoms or ions using one-sided soft x-ray photon fluxes.

Another scheme involves the flashlamp concept where the radiated flux from one plasma pumping another plasma creates conditions which result in coherent radiation in the soft x-ray regions. See A. V. Vinogradov, I. I. Sobel'man, and E. A. Yokov, Sov. J. Quantum. Electron 5, 59 (1975); B. A. Norton and N. J. Peacock, J. Phys. B 6, 989 (1975); J. P. Apruzese, J. Davis, and K. G. Whitney, J. Phys, B 11, L643 (1978); R. H. Dixon and R. C. Elton, J. Opt. Soc. Am. B 1, 232 (1984), and references therein. There are several cases where the coincidence between the pumping and absorbing lines is close enough to merit strong consideration as a possible lasing combination. For example, K-shell lines from Mg, Al, or Si are reasonably well matched to several fluorinelike Kr lines. Two such schemes utilize a Si XIII-Al III system and a Na X-Ne IX system. The Na-Ne scheme is particularly interesting because the lines match to two parts in 10^4 at a wavelength of 11 angstroms. An energy level diagram of this scheme is shown in FIG. 2.

In the Na-Ne approach, photons emitted from one element (Na) impinge upon and pump the upper lasing level of the second element (Ne). This is one of the most promising approaches but it has not succeeded because the conditions required in the pumped and pumping plasmas are drastically different and therefore difficult to acheve when they are in close physical proximity.

More specifically, the higher temperature that is present in order for the Na to function as a pump will propagate in a thermal wave over a finite time into the Ne creating an overall isothermal state which precludes the Ne from being at the lower temperature and density necessary to produce the desired x-ray lasing. This is particularly disastrous if the Ne is in contact with the Na. However, if the two materials are separated by any appreciable distance, then the efficiency of the system is lost due to solid angle effects.

SUMMARY OF THE INVENTION

Accordingly, one object of the present invention is to generate coherent x-rays.

Another object of the present invention is to use Na and Ne to produce x-rays.

Yet another object of the present invention is to provide a thermal buffer between Na and Ne to prevent the Na from heating and overionizing the Ne and precluding the generation of coherent x-rays.

These and other objects of the present invention are accomplished with an apparatus for generating coherent x-rays comprising: an Na layer; an Ne layer; a thermal transparent buffer layer located between and in contact with the Na layer and the Ne layer wherein the Ne layer is maintained at a lower temperature and density than the Na layer; a lower power laser to heat the Ne layer until Ne IX is present; and a higher power laser to heat the Na layer until Na X is present.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete appreciation of the invention and many of the attendant advantages thereof will be readily obtained as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings, wherein:

FIG. 1 is a schematic view of the Na-C-Ne x-ray lasing system.

FIG. 2 is a schematic drawing of the relevant energy level diagram for the Na-Ne scheme.

FIG. 3 is a graph of density and temperature profiles for one of several possible Na-C-Ne cases.

FIG. 4 is a graph of number density, temperature and He-like sodium ion density profiles for one of several possible Na-C-Ne cases.

FIG. 5 is a graph of the diagnosed intensity profile for the 11 angstrom line at the Na-C interface for three cases.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to the drawings, wherein like reference numerals designate identical or corresponding parts throughout the several views, and more particularly to FIG. 1 thereof, there is shown an apparatus for generating coherent x-rays. The apparatus 10 comprises an Na layer 12, an Ne layer 14, and a thermal nonopaque buffer layer 16 that is located between and in contact with the Na layer and the Ne layer. A laser 18 having power less than or equal to 10^{12} W/cm^2 heats the Ne layer and a higher power laser 20 having power greater than or equal to 5×10^{13} W/cm^2 heats the Na layer. The heated Na layer acts as a flashlamp to directly photopump the ablated Ne layer, thus generating coherent x-rays. The transparent thermal buffer layer 16 allows the Na layerand Ne layer to coexist at the drastically different conditions necessary for the x-ray lasing to occur since the Ne layer requires a lower temperature and density for operation than the Na layer. Without the thermal buffer layer 16, an isothermal condition would exist across the Na-Ne layers precluding the generation of x-rays. The lasing system is to be contained within an evacuated chamber with a frozen layer of Ne on one side of the Na layer buffer layer combination. (The chamber is kept cold enough to keep the Ne frozen until laser heating begins. The Ne has to be frozen in order for the electron density of the Ne to be above its critical density). The driving lasers enter the chamber through ports which are located in the chamber wall.

More specifically, the lower power laser 18 acts to create a tenuous Ne blowoff while the higher power laser 20 provides an energy source to heat the Na 12. The sodium then acts as a backlighting flashlamp for neon. Lasers which operate in the 0.25-1.0 μm range

are well suited for this task since absorption of the beam can be tailored to the requirements of the system. In actual operation absorption of laser 18 operating at a relatively low intensity in comparison with laser 20 will ablate the neon at a low temperature, typically about 100 eV. At the same time a higher-powered laser will heat the sodium plasma to a higher temperature which then serves as the backlighting pump source. Of course, within a finite time, the thermal wave will propagate through the sodium and into the neon. This isothermal state precludes the conditions which are necessary for achieving gain. To alleviate this problem, a third material 16 is placed between the Na-Ne interface. This material 16 acts as a thermal buffer while allowing the pumping radiation to pass through without significantly reducing the pumping intensity. The requirements the material 16 must fulfill are as follows. First, the material is chosen to be a solid which is both thick enough to absorb the thermal wave from the heated sodium 12 and keep it from reaching the neon 14. Thus, a material of approximately the same thickness and density as that of the original sodium is appropriate and allows for a thermal penetration time through the material to be roughly equal to that for the sodium. Second, the material should be relatively low in Z, where Z is the number of protons in the nucleus, so that opacity effects do not significantly impede the pumping line. A material such as carbon is ideal for this purpose. For example, the specific heat of carbon is approximately equal to that of the sodium and thus, allows the unwanted thermal energy of the sodium to be absorbed. Also, the photon cross section of cold carbon at 11 angstroms (i.e., the pumping line) is approximately 2×10^3 cm^2/g. Thus, for linear distances less than 2.2 μm, solid carbon (2.2 g/cm^3) can be considered to be thin to the pumping line. That is, the optical depth is less than or equal to one for this thickness and the attenuation of the pumping line is less than or equal to one e-folding. This distance can be lengthened if, for instance, CH is used in which case the corresponding carbon density is decreased. During the operation of the laser, the carbon layer 16 absorbs the energy of the thermal wave that results from the absorption of the laser beam of laser 20 in the sodium 12. Thus, the carbon is heated to above 10 eV as shown in FIG. 3. The absorption of this thermal energy by the carbon, however, prevents overheating of the neon.

In the determination of the thickness of the Ne layer 14 and the Na layer 12 the gain versus density relationships in each material are provided in J. P. Apruzese, J. Davis, and K. G. Whitney, J. Appl. Phys. 53, 4020 (1982). Optimally, the greatest gain for a given density of material is sought to maximize the efficiency of the system. The relationships given there, without presence of a thermal buffer layer, are also the controlling relationshiops when a thermal buffer layer is present. Thus the scale length should not be greater than 10 μm for ion densities on the order of 10^{20} cm^{-3}. (The scale length is a measure of the distance over which the density is changing. Thus, the distance over which the density drops from 10^{20} cm^{-3} to 10^{19} cm^{-3} would be 0.9 of a scale length. Hence, a 10 μm scale length would mean a drop from 10^{20} cm^{-3} to 10^{19} cm^{-3} over a distance of roughly 10 μm.) The scale length can increase to greater than 0.1 cm for ion number densities on the order of 10^{18} cm^3. (For a given amount of material within 10 μm at a density of 10^{20} cm^{-3}, expansion of the material so that the density is 10^{18} cm^{-3}, gives a distance of 10^3 μm or 0.1 cm.) FIG. 2 is a schematic diagram of the key energy levels for the Na-Ne scheme. The gain coefficients for the Ne IX 1s2p^{1}p-1s3d^{1}D and 1s2p^{1}P-1s4d^{1}D transitions peak near an ion density of 10^{20} cm^{-3}. The 1s3d^{1}D-1s4f^{1}D gain which peaks near 10^{19} cm^{-3}, subsequently drops off dramatically to less than unity at 10^{16} cm^{-3} but is still greater than 10 at 10^{18} cm^{-3}. The terminology of, for instance, 1s2p^{1}P is well known. The numbers in front of the lowercase letters represent principal quantum numbers. The lowercase letters, here s and p, represent the angular momentum associated with the principal quantum numbers in the atomic configuration. The uppercase symbol, here P, designates the total atomic angular momentum. The superscripted number next to that symbol, here 1, refers to the multiplicity of the configuration. This number takes on the value 2S+1 were S is the total spin of the atom. When more than one electron occupies a given angular momentum value for a principal quantum number, a superscript is used to designate the number of electrons as in the 1s^2 ^{1}S ground state. FIG. 2 shows that Na X, when it is heated by laser 20, has a resonant transition from a ground state of 1s^2 ^{1}S to an excited state of 1s2p^{1}P at 11.0027 angstroms and then returns to the ground state of 1s^2 ^{1}S, but in the process of returning to the ground state releases a photon at 11.0027 angstroms. Referring to the Ne X energy levels shown in FIG. 2, the Ne IX is resonantly photo-pumped at 11.0003 Angstroms from ground state of 1s^2 ^{1}S to 1s4p^1 ^{1}P. The resulting inversion results in transitions at 58 angstroms (1s2p^{1}P-1s4d^{1}D), 230 angstroms (1s3d^{1}D-1s4f^{1}D) and 82 angstroms (1s2p^{1}P-1s3d^{1}D). It is to be noted that the Na layer contains a significantly greater mass than the Ne layer which must be cryogenic at solid densities. Hence, the choice of Na for use as the pumping source allows for easier target construction and manipulation.

Only Na X and Ne IX are of interest in the Na-Ne scheme of x-ray lasing. The roman numeral after the element represents one plus the number of free electrons that have been disassociated from the element to form the plasma of the material. The lasers 18 and 20 are tuned to the proper intensity (see FIG. 3) to heat the layers 12 and 14 to maximize the production of Na X or Ne IX as well as to pump the Na X 1s^2 ^{1}S to 1s2p^{1}P transition.

The layers 12 and 14 are solid Na and Ne, respectively, at the start of heating, but as heating continues and the respective plasmas form, the stages of free electrons preceding the Na X level and the Ne IX level are reached and passed. If care is not taken, too much heating will cause the desired Ne IX level to be burned through eliminating any further x-ray production. This can be avoided by limiting the laser and not allowing the Ne temperature (see FIG. 3) to reach too high of a value. (It should be noted that if a source is used to pump the Ne IX other than Na X, then population inversion is not achieved. The excited electrons are trapped at lower energy levels and essentially no x-ray generation occurs.)

The thickness, d, of the Ne layer of the ablated neon can be scaled as A/N for a fixed optical depth where A is a constant and N is the ion density. The optical depth is a function of the constant A, thickness, d, and density, N, given by $\tau = ANd$. Thus for a fixed optical depth, the thickness of the layer varies inversely with density. The thickness of the layer can then by scaled with density using the maximum allowed optical depth. The maximum 1-2 resonance line optical depth before significant

reduction in population inversion occurs has been determined by P. C. Hagelstein, Lawrence Livemore National Laboratory Report UCRL-53100 (1981) to be approximately 5. This requires an ablated blowoff with a scale length not greater than the 10 μm for ion densities of 10^{20} cm^{-3}. This scale length can be increased to greater than 0.1 cm for number densities on the order of 10^{18} cm^{-3}.

As mentioned above, the Na-Ne combination for lasing requires a difference in the temperature and densities of the Ne and Na layer. The temperature of the lasing neon must be kept low enough to prevent burnout of the Ne IX population. At a density of 10^{18} cm^{-3} the maximum fractional population for Ne IX occurs at approximately 65 eV in the presence of the pump radiation. On the other hand, the pumping plasma (in this case Na) is most favorable when it is an optically thick plasma with a kinetic temperature of about 300 eV. In short, what is desired is a hot dense pumping plasma irradiating a cooler lasing plasma which is optically thin along one axis. The density and temperature profiles for the Ne-C-Na system at 100 psec after the laser peak is shown in FIG. 3. In FIG. 3, T is the temperature (where T_e is the electron temperature and T_i is the ion temperature) and ρ is the density, both being a function of distance from the C layer, for the case, of many possible cases, where the Na/C thickness is 0.5 μm/0.5 μm, the peak laser intensity is 5×10^{13} W/cm^3, the pulse time is 200 psec, the line center pumping intensity is 2.0×10^3 $ergs/cm^2$ sec Hz and the line width at half center value is 3.0×10^{14} (Hz). The region where absorption of the line occurs in neon is seen to be roughly 100 eV for the electrons. The density in this region passes through the value 10^{-3} g/cm^3 (or 3×10^{19} $ions/cm^3$) which is near the optimum density for gain. The sodium, on the other hand, has a temperature which varies between 100 eV and 1 keV at a density of more than 10^{-2} g/cm^3. This provides a strong punping source of He-like sodium. FIG. 4 shows the He-like ion density of the Na plasma. The He-like density is seen to peak at the carbon interface. A total of three cases is shown in table 1, which is a table of parameters for three Na-C targets. In these three cases both sides of the target are irradiated by lasers operating at 1.06 μm. The intensity on the Ne side is well below that on the Na side and is typically on the order of 10^{12} W/cm^2. If necessary the low power laser on the neon can be turned off to prevent overheating.

TABLE 1

Case	Na/C thickness (m)	Peak laser intensity (W/cm^2)	Pulse time FWHM (psec)	Line center pumping Intensity ($ergs/cm^2$ sec Hz)	Pump line width at half center value (Hz)
I	0.5/0.5	5×10^{13}	200	2.0×10^3	3.0×10^{14}
II	0.1/0.5	2.5×10^{13}	200	9.6×10^2	2.0×10^{14}
III	0.1/0.5	1×10^{13}	300	6.7×10^2	2.2×10^{14}

Here pulse time is the full-width-half-maximum (FWHM) time over which the external lasers are on in psec (10^{-12} sec); line center pumping intensity is the intensity at the center of the Na X 11.0027 angstrom pumping line; and pumping line width is the width in Hz of the pumping line at half the maximum value at center.

A corresponding graph (see FIG. 5) shows the post processed intensity profile for the 11 angstrom pumping line at the Na-C interface. The three cases of table I are shown along with the inferred Rochester experimental profile in FIG. 5. The times for case I and case II are 100 psec after the peak of the Gaussian-shaped laser pulse. The time for case III is 300 psec, which is the rise time for the linear ramped pulse. In a 300 psec linear ramped pulse, the external lasers rise to their full values linearly in 300 psec and are subsequently held constant. The Rochester experimental profile is the diagnosed intensity profile of only a small amount of Na in a glass microballoon which has been heated by a laser. The other three cases, all having a much greater amount of Na, have a capped peak to a certain degree because of self-absorption at 11 angstroms in the cooler surrounding Na.

Obviously, numerous (additional) modifications and variations of the present invention are possible in light of the above teachings. It is therefore to be understood that within the scope of the appended claims, the invention may be practiced otherwise than as specifically described herein.

What is claimed as new and desired to be secured by Letters Patent of the United States is:

1. A lasing system for generating frequency coherent x-rays, comprising:

a sodium layer;

a first heating means for heating said sodium layer until Na X is present;

a neon layer, wherein said neon layer is kept frozen until laser heating begins;

a second heating means for heating said neon layer until Ne IX is present, so that Ne IX is pumped by Na X to achieve the necessary population for lasing to occur;

a thermal transparent buffer layer located between and in contact with said sodium and neon layers, wherein said buffer layer absorbs thermal waves from said sodium layer and wherein said neon layer is maintained at a lower temperature and density than said sodium layer for lasing to occur; and

means for containing said sodium-buffer-neon layered combination.

2. The lasing system as recited in claim 1 wherein the sodium layer is at least 0.5 μm thick, the thermal buffer layer is carbon and is at least 0.5 μm thick, and the neon layer has a maximum resonance line optical depth of less than 5.

3. The lasing system as recited in claim 1 wherein said first heating means for heating said neon layer until Ne IX is present comprises a laser having power less than or equal to 10^{12} W/cm^2 and said second heating means for heating said sodium layer until Na X is present comprises a laser having a power greater than or equal to 5×10^{13} W/cm^2.

4. A method for generating frequency coherent lasing in the x-ray wavelength comprising the steps of:

heating a sodium layer until Na X is present;

heating a frozen neon layer until Ne IX is present, wherein said frozen neon layer is kept frozen until laser heating begins;

providing said neon layer in close proximity to said sodium layer with a transparent thermal buffer

layer in between and in contact with both of said sodium and neon layers for absorbing a thermal wave produced in said sodium layer, wherein said neon layer is maintained at a lower temperature and density than said sodium layer for lasing to occur, whereby said neon layer is photopumped with radiation from said heated sodium layer to produce lasing of said neon layer.

5. The method as recited in claim 4 wherein said step of heating said sodium layer is performed using a laser having power greater than 5×10^{13} W/cm^2, and wherein said step of heating said neon layer comprises lasing said frozen neon layer with a laser having power less than or equal to 10^{12} W/cm^2.

6. The method as recited in claim 5 wherein said sodium layer is at least 0.5 um thick, said buffer layer is carbon and is at least 0.5 um thick, and said neon layer has a maximum resonance line optical depth of less than 5.

* * * * *

United States Patent [19]

Nighan et al.

[11] **Patent Number: 4,817,096**

[45] **Date of Patent: Mar. 28, 1989**

[54] **MULTIPLE WAVELENGTH EXCIMER LASER**

[75] Inventors: William L. Nighan, Manchester, Conn.; Roland A. Sauerbrey; Frank K. Tittel, Both of Houston, Tex.

[73] Assignee: United Technologies Corporation, Hartford, Conn.

[21] Appl. No.: 240,370

[22] Filed: Aug. 29, 1988

Related U.S. Application Data

[63] Continuation of Ser. No. 844,450, Mar. 26, 1986, abandoned.

[51] Int. Cl.[4] H01S 3/30; H01S 3/22; H01S 3/223; H01S 3/097

[52] U.S. Cl. 372/5; 372/23; 372/55; 372/57; 372/60; 372/83; 372/99

[58] Field of Search 372/5, 23, 55, 57, 60, 372/83, 99

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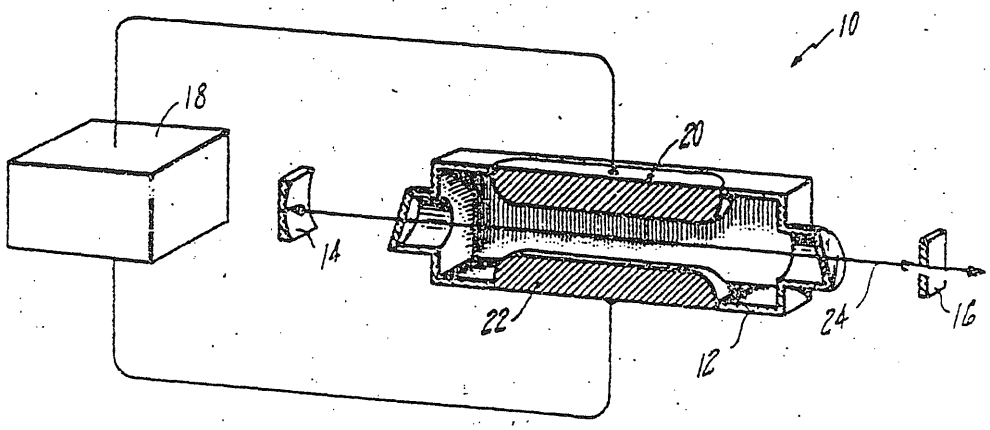
Primary Examiner—Eugene R. Laroche
Assistant Examiner—Michael Shingleton
Attorney, Agent, or Firm—Eric W. Petraske

[57] ABSTRACT

A transverse electrically excited gas laser comprises a mixture of rare gases and a fluorine donor at selected partial pressures so as to permit UV and/or visible rare gas-halide laser oscillation at two or more wavelengths simultaneously.

6 Claims, 3 Drawing Sheets



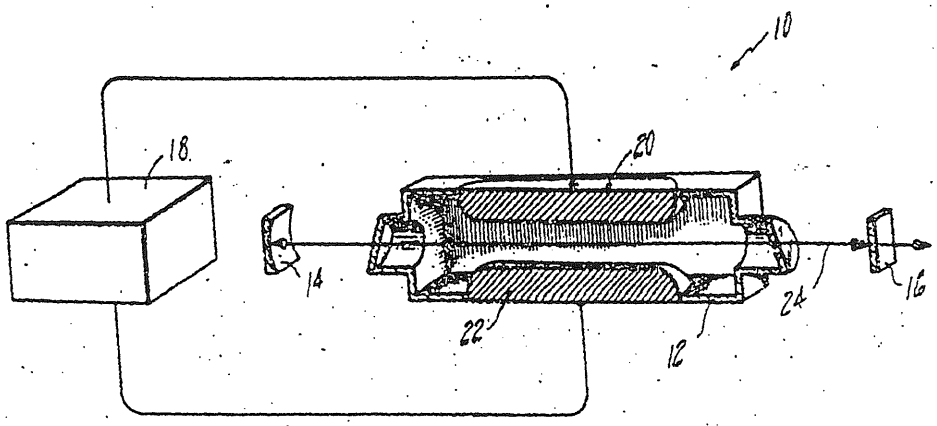
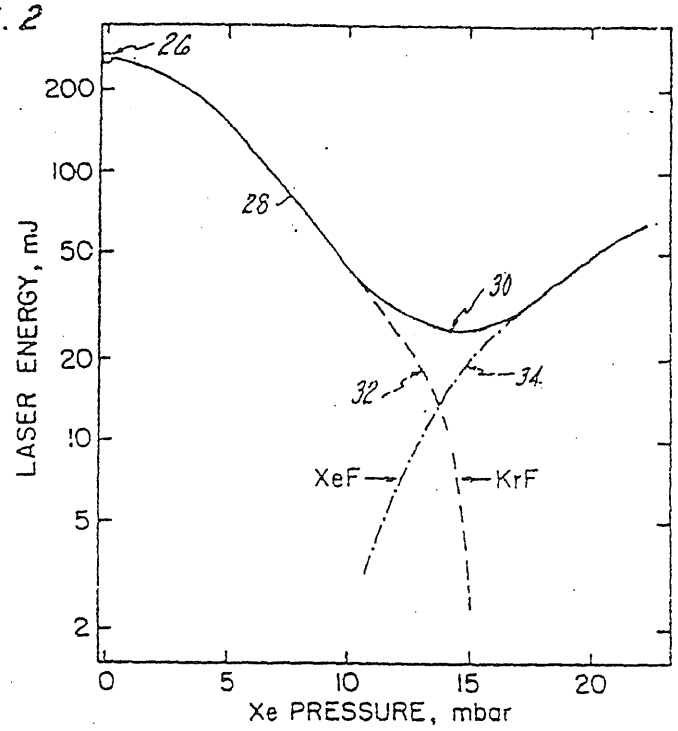


FIG. 1

FIG. 2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28
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32
34
XeF
KrF
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20
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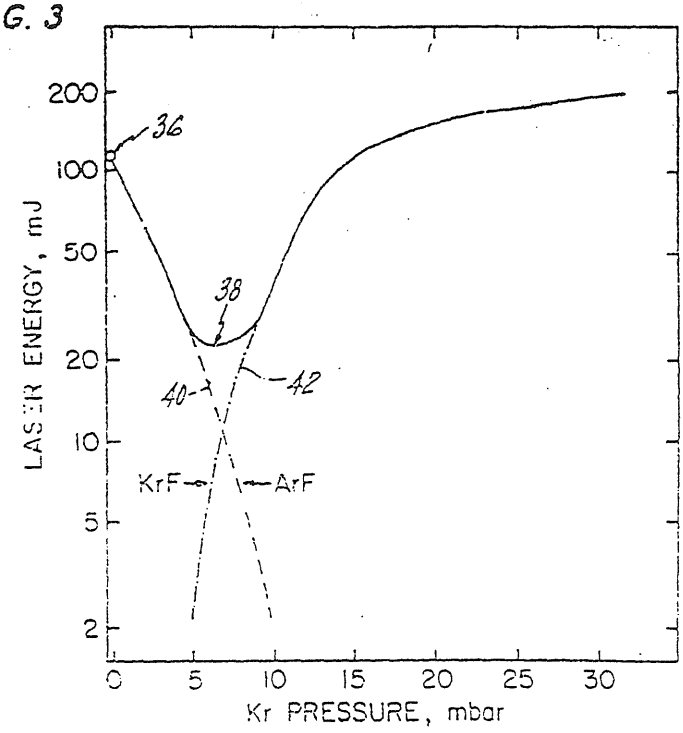
5
10
15
20
Xe PRESSURE, mbar

FIG. 3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KrF
ArF
LASER ENERGY, mJ
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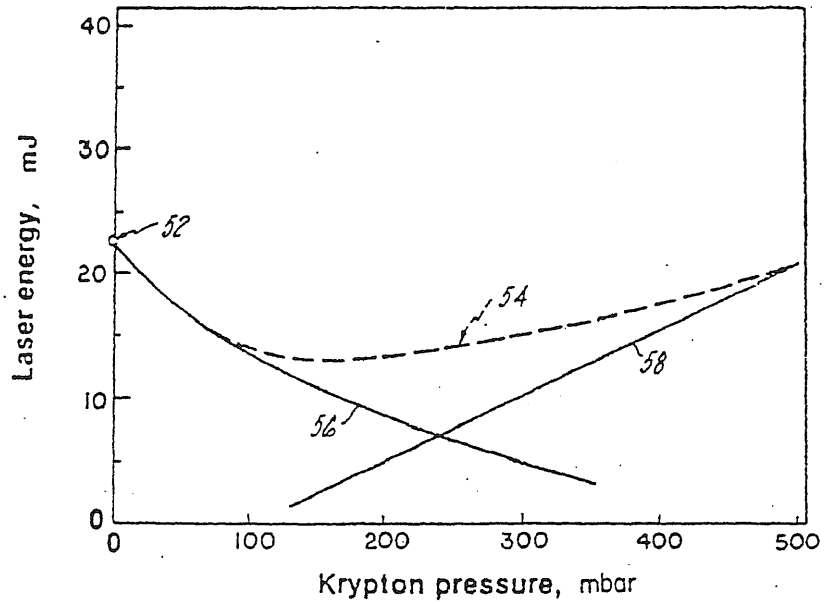
30
Kr PRESSURE, mbar

FIG. 4


40
30
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Laser energy, mJ
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200
300
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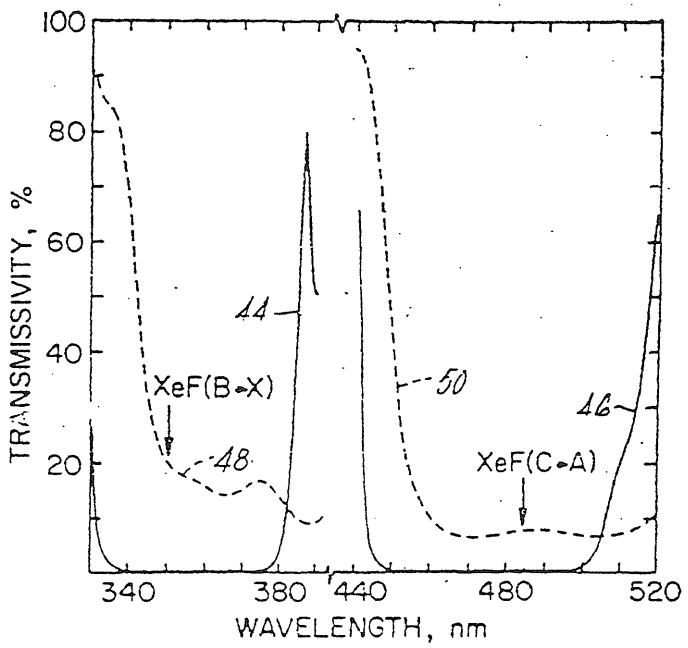
500
Krypton pressure, mbar

FIG. 5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46
XeF(C-A)
340
380
440
480
520
WAVELENGTH, nm

MULTIPLE WAVELENGTH EXCIMER LASER

The Government has rights in this invention pursuant to Contract No. N00014-76-C-0847 awarded by the Department of the Navy.

This is a continuation of Ser. No. 844,450, filed Mar. 26, 1986, abandoned.

DESCRIPTION

TECHNICAL FIELD

This invention relates to electrically excited lasers having wavelengths in the UV/visible region of the spectrum and more particularly to lasers of the rare gas-halide class.

BACKGROUND ART

Excimer gas lasers are part of a family of electronic transition lasers that produce powerful laser pulses having wavelengths in the UV/visible region of the electromagnetic spectrum. The term excimer is used to describe the lasing species which is an excited molecule that is not stable in the ground electronic state. Excimer molecules do not exist in the initial gas mixture but are produced by action of an electrical excitation such as a discharge acting on the initial mixture constituents. This feature distinguishes excimer lasers from other gas lasers.

Of the excimer lasers, those of the rare gas-halide class are the most important because they can be produced with high efficiency using readily available technology such as by the electric discharge method. Examples of rare gas-halide excimer lasers are ArF, KrF, XeCl and XeF generating UV wavelengths of 193 nm, 248 nm, 308 nm and 351 nm, respectively. Lasers of this type are produced commercially and are used for a wide variety of industrial, medical and scientific applications. Their properties are reviewed in comprehensive summary articles by J. Hecht appearing in *Lasers and Applications*, Volume II, page 43, December 1983 and by H. Pummer appearing in *Photonics Spectra*, Vol. 19, p. 73, May 1985.

There are many applications in areas such as spectroscopy, optical diagnostics, materials processing and medicine for which UV or visible laser radiation at more than one wavelength is needed. However the discharge excited rare gas-halide lasers currently known are capable of producing only one wavelength at a time. For example, in order to produce 193 nm radiation typical of the ArF laser, a gas mixture containing Ar and a fluorine donor such as F_2 is used in the laser chamber. To generate another wavelength such as 351 nm radiation from XeF the gas mixture must be changed to one containing Xe and F_2. Therefore a single laser system can produce only one wavelength at a time. For applications requiring two or more UV wavelengths simultaneously, a separate laser system is required for each wavelength, introducing considerable additional cost and complexity.

Moreover, because rare gas-halide lasers generate very short duration pulses on the order of 10 nsec, synchronization of the laser pulses from different laser systems producing different UV wavelengths is a serious problem. To supplement the UV laser, other applications require a separate visible laser for spatial alignment or where safety considerations require that the laser beam be seen by the eye.

J. M. Hoffman, et al have disclosed in *Applied Physics Letters*, Vol. 28, p. 538, May 1, 1976, the feasibility of achieving simultaneous laser oscillation on the 193 nm ArF transition and the 248 nm KrF transition. However, in that work laser excitation was provided by a high energy electron beam accelerator in which a beam of electrons having an energy of 2 MeV was confined by an externally applied axial magnetic field so as to guide the electron beam longitudinally through the laser chamber. This laboratory means of providing excitation was capable of being fired only ten times per day, and is so complex as to preclude use in practical applications. Means to generate more than one UV wavelength at the same time from a single repetitively pulsed, discharge excited rare gas-halide laser, or to generate a UV wavelength and a visible wavelength simultaneously from such a laser are unknown in the prior art.

DISCLOSURE OF INVENTION

An object of the present invention is to provide an excimer laser generating UV or UV/visible radiation simultaneously at more than one wavelength.

According to the present invention a multiple wavelength excimer laser includes an enclosure disposed about an optic axis and having a longitudinal interior cavity. Within the interior cavity is a gas mixture comprising a buffer gas, a halogen donor gas and a gas comprising at least two elements selected from the group argon, krypton and xenon. Also included is a means for laser excitation that generates an electric field transverse to the optic axis producing a gas discharge in the gas mixture. The laser excitation means further resonates radiation in said gas discharge simultaneously producing laser radiation at a plurality of wavelengths approximately between 150 and 500 nm.

BRIEF DESCRIPTION OF DRAWINGS

FIG. 1 is a simplified block diagram partially in section and partially in perspective of a multiple wavelength excimer laser provided according to the present invention;

FIG. 2 is a drawing showing the dependence of total UV laser energy as well as separate KrF and XeF laser energies as a function of Xe pressure for a multiple wavelength excimer laser provided according to the present invention;

FIG. 3 is a drawing showing the dependence of total UV laser energy as well as separate ArF and KrF laser energies as a function of Kr pressure for an alternative multiple wavelength excimer laser provided according to the present invention;

FIG. 4 is a drawing showing the dependence of the total laser energy as well as the 351 nm XeF and 480 nm XeF laser energies as a function of Kr pressure for an alternative embodiment of a multiple wavelength excimer laser provided according to the present invention simultaneously producing visible and UV radiation; and

FIG. 5 is a drawing showing the wavelength dependence of the transmission of the highly reflecting mirror and outcoupler used in the UV/visible excimer laser of FIG. 4.

BEST MODE FOR CARRYING OUT THE INVENTION

FIG. 1 is a simplified block diagram partially in section and partially in perspective of a multiple wavelength excimer laser 10 provided according to the present invention. Laser chamber 12 includes an optical

cavity comprised of an end mirror 14 that is highly reflecting for UV/visible laser wavelengths and an outcoupler 16 having a reflectivity selected to be optimum for the laser wavelengths of interest. In the best mode embodiment, the outcoupler comprises a CaF_2 or MgF_2window, having a reflectivity of 5-10% in the UV/visible region. Alternatively, the outcoupler can be a mirror having a preselected reflectivity at specified UV and/or visible wavelengths. The laser chamber is constructed of halogen-compatible materials such as fluorocarbon insulators and easily passivated metals such as aluminum and nickel and is usually equipped with a gas circulation system (not shown) typically comprised of a fan, a heat exchanger and a filter so that a fresh, clean gas mixture (not shown) is always present. In the best mode embodiment the laser chamber comprises a Lambda Physik EMG 100 series excimer laser or equivalent. The gas mixture is of a type described hereinafter that is specifically tailored to produce simultaneous multiple wavelength rare gas-halide laser oscillation.

In the best mode embodiment, the gas mixture is excited by supplying pulsed, high voltage electrical energy from conventional electric power supply 18 to electrodes 20, 22 thereby producing an avalanche electric discharge transverse to optic axis 24. Electrodes 20, 22 are fabricated of a halogen-compatible, sputter-resistant material such as nickel and are similar in design to electrodes found in conventional excimer lasers.

Power supply 18 typically includes a very fast, low inductance circuit designed to provide a source of uniform preionization, such as UV radiation, thereby ensuring the formation of a stable, uniform electric discharge when a main voltage is applied between electrodes 20, 22. The actual pumping of the excimer gas mixture occurs by discharging a high voltage capacitor through a suitable switch such as a thyratron which comprise part of the circuitry of the power supply. Those skilled in the art will note that other, alternative configurations of the laser chamber and alternative methods of providing excitation such as with microwaves, an electron-beam or other energetic particles may be equivalently substituted.

FIG. 2 is a diagram illustrating total UV laser energy as well as separate KrF and XeF laser energies as a function of Xe partial pressure for a multiple wavelength excimer laser provided according to the present invention. To measure the total UV laser energy at each Xe concentration, a conventional calibrated pyroelectric energy meter was employed while the spectral content of the UV laser was measured using inteference and color glass filters as described by R. A. Sauerbrey, et al in the *IEEE Journal of Quantum Electronics*, Vol. QE-22, p. 230, February 1986, and expressly incorporated by reference herein.

In the best mode embodiment, the laser chamber (12, FIG. 1) is initially filled with a gas mixture approximately comprised of 6 mbar F_2, 150 mbar Kr and He at an initial total pressure of 2.5 bar. As indicated by point 26, this gas mixture provides efficient, high power KrF laser pulses at a wavelength of 248 nm when excited in an electric discharge laser apparatus. As Xe is added to the mixture, the total UV laser output energy indicated by curve 28 decreases until a minimum (30) is found for a Xe pressure of about 14 mbar.

For Xe pressures between 10 mbar and 16 mbar a laser generates both 248 nm KrF laser radiation (curve 32) and 351 nm XeF radiation (curve 34) simultaneously with both laser pulses overlapping temporally and having a duration of about 10 nsec. For Xe pressure of about 14 mbar both the 248 nm KrF laser and the 351 nm XeF laser have pulse energies of about 10 mJ corresponding to an overall efficiency of about 0.2%. Decreasing the Xe pressure below 14 mbar causes the 248 nm KrF laser to dominate and increasing the Xe pressure above 14 mbar causes the XeF laser to dominate showing that changes in the Xe pressure can be used to control the relative energies of the simultaneously occurring 248 nm and 351 nm laser pulses.

For the lasers producing the curves of FIG. 2 the outcoupler (16, FIG. 1) was comprised of CaF_2 having an 8% reflectivity at both 248 nm and 351 nm. However, significantly improved multiple wavelength laser energy can be obtained by replacing the outcoupler by a mirror having a 70% reflectivity at both wavelengths. Greater improvement occurs with a mirror designed to have separately optimized reflectivities at each of the 248 nm and 351 nm wavelengths, either over the entire planar surface of the mirror or in zones such that the 248 nm and 351 nm laser beams are generated in a side-by-side manner rather than colinearly, as in the present embodiment.

FIG. 3 is a diagram showing the total UV laser energy as well as separate ArF and KfF laser energies as a function of Kr pressure for another multiple wavelength excimer laser provided according to the present invention. The total UV energy and spectral content of the laser are measured by conventional techniques as described hereinabove. The laser comprises the apparatus described hereinabove with respect to FIG. 1 and has a gas mixture that includes 7.5 mbar F_2, 350 mbar Ar and He at an initial total pressure of 2.2 bar. Efficient, high power ArF laser pulses have a wavelength of 193 nm as indicated by point 36. As Kr is added to the gas mixture, the total UV laser output decreases until a minimum (38) is established for a Kr pressure of 6 mbar. At this Kr pressure both the 193 nm ArF laser and a 248 nm KrF laser operate simultaneously with temporally overlapping laser pulses. As indicated by curves 40 and 42 of ArF and KrF respectively, the relative energies for the 193 nm and 248 nm pulses are selectable by varying the Kr pressure around 6 mbar.

It is apparent to those skilled in the art that other simultaneously occuring UV wavelength combinations are also possible such as 193 nm ArF and 351 nm XeF laser radiation from lasers which comprise rare gas-halide mixtures containing Ar, Xe and F_2; 193 nm ArF, 248 nm KrF and 351 nm XeF laser radiation from mixtures containing Ar, Kr, Xe and F_2; also 222 nm KrCl and 308 nm XeCl laser radiation from mixtures containing Kr and Xe and a suitable chlorine donor such as HCl.

The UV laser action described hereinabove is the result of transitions between the B and X states of the rare gas-halide excimer (the letter B and X being conventional references to particular rare gas-halide electronic states). However, in addition to the XeF 351 nm UV B→X transition, the XeF excimer molecule also exhibits broadband laser action on another transition designated as the C→A transition. Unlike the UV B→X transition, the broadband XeF (C→A) transition is centered in the visible region of the spectrum at a wavelength of 480 nm. A particularly important difference beween the visible 480 nm XeF (C→A) laser transition and the UV 351 nm XeF (B→X) laser transition is the fact that the former transition always exhibits much

lower optical gain than is typical of UV rare gas-halide B→X lasers. Therefore, in order to provide simultaneous UV and visible laser oscillation from the XeF excimer transitions excited in a single laser chamber an outcoupler must be provided that has separately optimized transmission and reflection properties at each of the 351 nm and 480 nm wavelengths, as described by R. A. Sauerbrey, et al in the *IEEE Journal of Quantum Electronics*, Vol. QE-21, p. 418, May 1985, and expressly incorporated by reference herein.

FIG. 4 is a drawing showing the dependence of the total laser energy as well as the 351 nm XeF and 480 nm XeF laser energies as a function of Kr partial pressure for an alternative embodiment of a multiple wavelength excimer laser provided according to the present invention simultaneously producing visible and UV radiation. The laser is similar to that described hereinabove with respect to FIG. 1 and is characterized by an electron beam means of transverse electrical excitation as well as comprising an outcoupler having optimized transmission properties at each of the 351 nm and 480 nm XeF wavelengths.

FIG. 5 is a drawing showing the wavelength dependence of the transmission of the outcoupler and highly reflecting mirror used in the laser described hereinabove with respect to FIG. 4. Curves 44 and 46 illustrate the mirror transmission in the wavelength regions 330–385 nm and 440–520 nm, respectively in the UV and visible regions of the spectrum. Curve 48 illustrates that the outcoupler transmission at the 351 nm wavelength of the XeF (B→X) transition is about 20%. As indicated by curve 50, the outcoupler transmission is approximately 10% between 460 nm and 510 nm throughout which the broadband XeF (C→A) transition oscillates. The laser described with respect to FIG. 4 includes a gas mixture comprised of 10.5 mbar NF_3, 1.3 mbar F_2, 10.5 mbar Xe and Ar at a total pressure of 6.5 bar. Under these conditions 351 nm XeF laser radiation is produced using electron-beam excitation (point 52 in FIG. 4). Upon addition of Kr the total laser energy decreases until a broad minimum (point 54) is established for Kr pressure in the 100 to 200 mbar range. For this range of Kr pressure both the 351 nm and 480 nm XeF excimer transitions are oscillating simultaneously, as indicated by curves 56 and 58 respectively. The relative intensity of the two laser beams are selected by simply changing the Kr pressure. Moreover, the laser efficiency is on the order of 0.3% when both the UV and visible lasers are operating simultaneously.

Simultaneous oscillation of both XeF excimer transitions in a single medium is particularly important since the C→A 480 nm transition is visible. This means that by selecting gas mixtures and by designing the outcoupler to be compatible with both 351 nm and 480 nm laser oscillation, efficient, high power 351 nm XeF laser radiation can be generated simultaneously with a weak 480 nm laser beam that is visible to the eye. The ability to effectively render a UV laser beam at 351 nm visible by the temporal and spatial superposition of a 480 nm laser beam will be useful in a variety of applications. Other outcouplers, suc has side-by-side mirrors or zones on a single mirror designed to separately optimize the transmission characteristics of the 351 nm and 480 nm laser beams will be obvious to those skilled in the art.

Similarly, although the invention has been shown and described with respect to a best mode embodiment thereof, it should be understood by those skilled in the art that various other changes, omissions and additions thereto may be made therein without departing from the spirit and scope of the invention.

We claim:

1. A multiple wavelength excimer laser comprising:
   enclosure means having an optically transmissive portion and having a longitudinal interior region disposed about at least one optical axis;
   gas mixture means contained within said region comprising predetermined quantities of a buffer gas, xenon, and a fluorine donor gas;
   excitation means for exciting said gas mixture means to produce quantities of xenon fluoride excimer in the excited B and C states;
   optical means disposed along said at least one optical axis and bounding a predetermined portion of said gas mixture means to form an optical cavity having predetermined reflectivity characteristics in the ultraviolet and the visible portion of the spectrum said gas mixture means, said excitation means, and said optical means being interrelated such that said quantities of xenon fluoride excimer form population inversions for both said B→X and C→A transitions and such that said gas mixture means within said optical cavity has sufficient optical gain on both the B→X transition and the C→A transition of xenon fluoride such that the energy conversion efficiencies of said visible and ultraviolet radiation differ by less than a factor of 10, whereby ultraviolet radiation in the B→X band and visible radiation in the C→A band are amplified simultaneously within said optical cavity.

2. A laser according to claim 1, in which said optical means is configured such that said optical axis is the optical axis for both said ultraviolet and visible radiation.

3. A laser according to claim 2, in which said optical means includes reflective means disposed along said optical axia and having predetermined reflectivity in the range of 350 nm and the range of 450–520 nm adapted to produce efficient radiation production in both the visible and the ultraviolet simultaneously.

4. A laser according to claim 1, in which said optical means is configured such that said ultraviolet and visible radiation each have an optical axis passing within said gas mixture means, whereby said optical means forms a first cavity for resonating ultraviolet radiation and a second cavity for resonating visible radiation.

5. A laser according to claim 4, in which said gas mixture means includes krypton at a predetermined pressure such that said optical cavity has optical gain on the 248 nm krypton fluoride transition and also on at least one transition of xenon fluoride.

6. A laser according to claim 5, in which said at least one transition is within the C→A band of xenon fluoride.

* * * * *

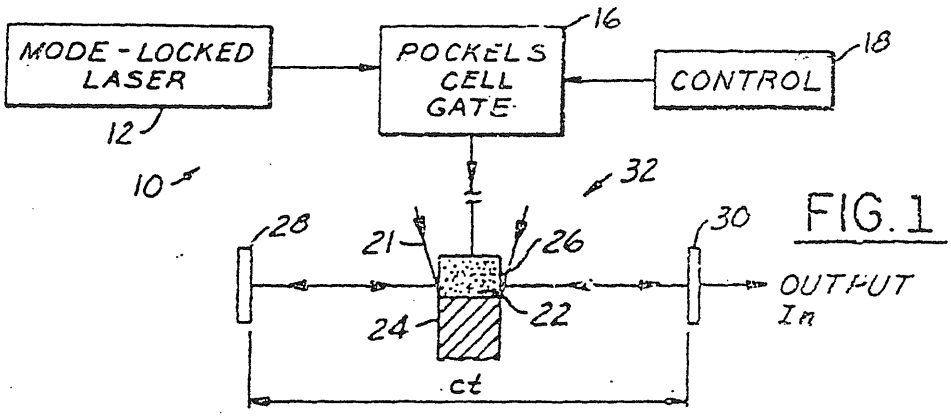

FIG. 1

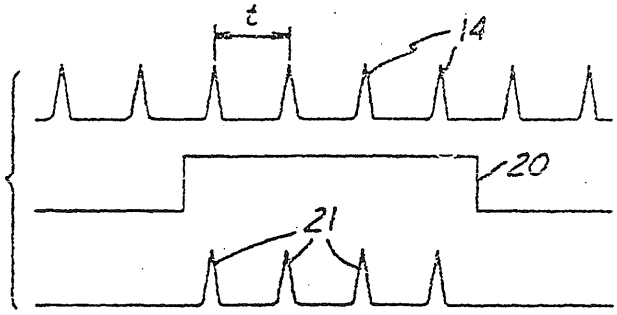

FIG. 2

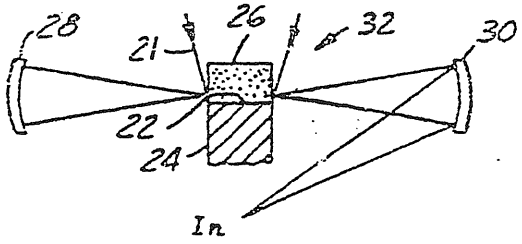

FIG. 3

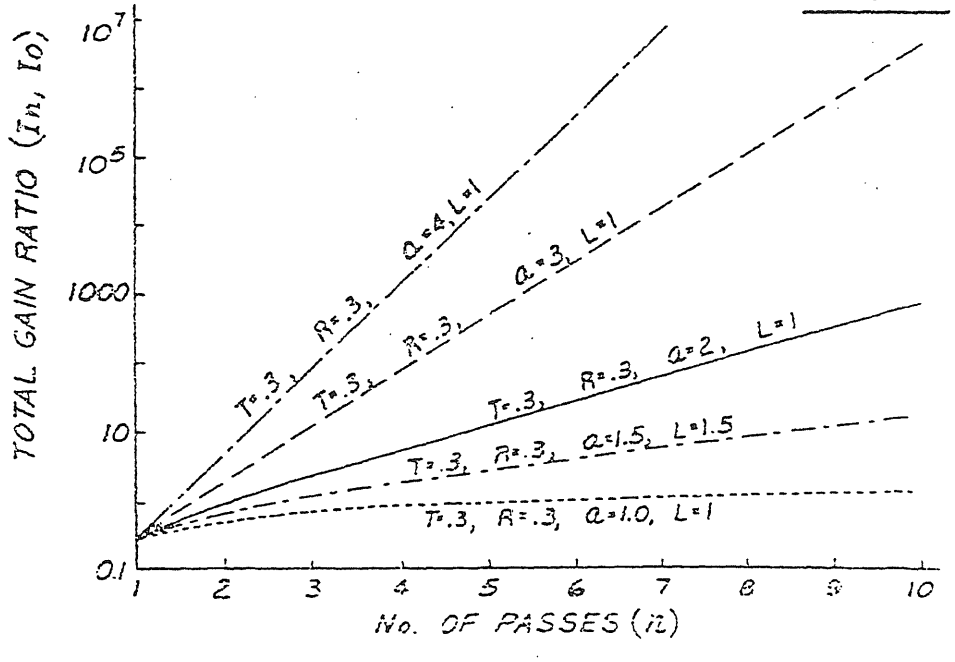

FIG. 4

United States Patent [19]

Charatis

[11] Patent Number: 5,065,108

[45] Date of Patent: Nov. 12, 1991

[54] REGENERATIVE CAVITY X-RAY LASING AMPLIFIER

[75] Inventor: George Charatis, Ann Arbor, Mich.

[73] Assignee: KMS Fusion, Inc., Ann Arbor, Mich.

[21] Appl. No.: 367,310

[22] Filed: Jun. 16, 1989

[51] Int. Cl.[5] H01S 3/09; H01S 3/30

[52] U.S. Cl. 359/333; 372/5; 372/70

[58] Field of Search 372/5, 18, 70, 108; 330/4.3

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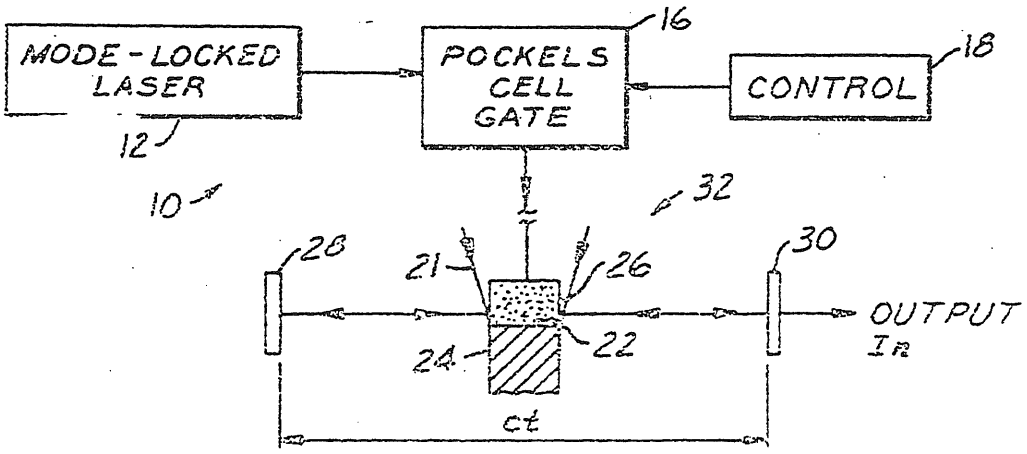
Primary Examiner—Nelson Moskowitz

Attorney, Agent, or Firm—Barnes, Kisselle, Raisch, Choate, Whittemore & Hulbert

[57] ABSTRACT

A regenerative cavity X-ray lasing oscillator and method in which an X-ray laser target is positioned between a pair of opposed coaxial mirrors at predetermined fixed spacing and forming an X-ray cavity. A series of light pulses is directed onto the target surface at predetermined fixed time intervals that correspond to spacing between the mirrors. Each light pulse ablates a portion of the target surface to form an ion plasma adjacent to the target surface of a character and composition for spontaneous emission of X-ray energy along the axis of the cavity. Such X-ray energy oscillates in the cavity and is amplified upon each passage through the plasma. One of the mirrors is constructed for extracting the amplified X-ray laser energy from the cavity.

14 Claims, 2 Drawing Sheets



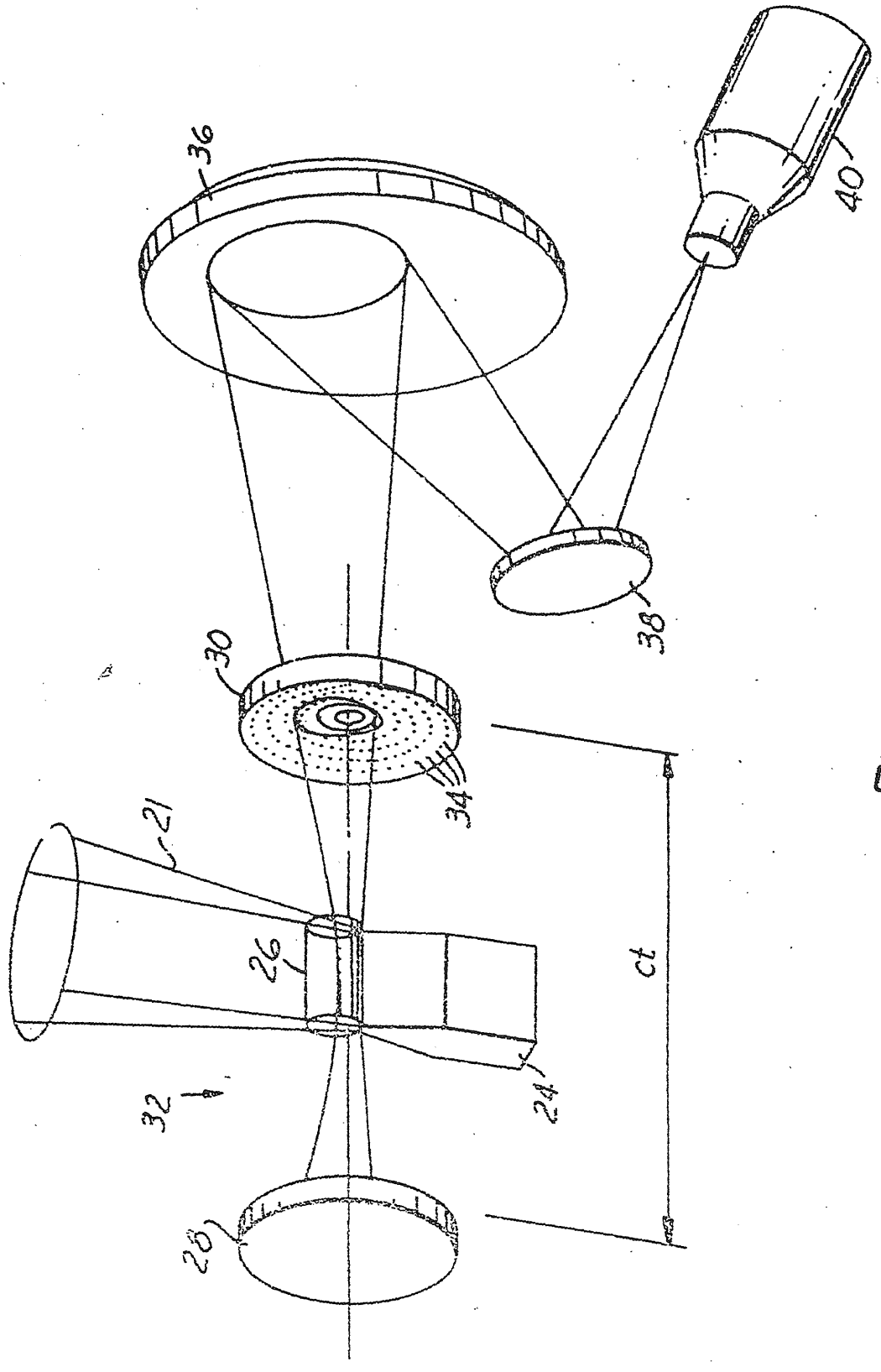


FIG. 5

REGENERATIVE CAVITY X-RAY LASING AMPLIFIER

The present invention is directed to X-ray lasers, and more particularly to a method and apparatus for boosting or amplifying X-ray laser output.

U.S. Pat. Nos. 4,731,786 and 4,827,479 disclose X-ray lasers in which a flat target surface of selected composition, such as selenium, is illuminated by a high-intensity laser beam to ablate a portion of the target surface and form a generally cylindrically shaped plasma adjacent to the target surface. This plasma contains neon-like ions that spontaneously emit X-ray radiation along a line orthogonal to the illumination axis and parallel to the axis of the cylindrical plasma. It is a general object of the present invention to provide an X-ray lasing amplifier and method, of the type disclosed in the noted patents, that provide enhanced laser gain and efficiency.

The invention, together with additional objects, features and advantages thereof, will be best understood from the following description, the appended claims and the accompanying drawings in which:

FIG. 1 is a functional block diagram of an X-ray laser in accordance with one presently preferred embodiment of the invention;

FIG. 2 is a graphic illustration of various timing and control pulses useful in describing operation of the embodiment of the invention illustrated in FIG. 1;

FIG. 3 is a fragmentary functional block diagram of a modified embodiment of the invention;

FIG. 4 is a graph that illustrates output characteristics of the embodiment of the invention illustrated in FIG. 1; and

FIG. 5 is a fragmentary functional block diagram of another embodiment of the invention.

The disclosures of U.S. Pat. Nos. 4,731,786 and 4,827,479 are incorporated herein by reference for background discussion of X-ray laser structure, theory and operation.

In a first laser system 10 (FIG. 1) in accordance with the present invention, a mode-locked laser 12 provides a continuing series of output light pulses 14 (FIG. 2) at uniform inter-pulse spacing t (FIG. 2) determined by laser cavity length. A Pockels cell gate 16 receives the pulses 14 from laser 12 and is responsive to a signal 20 from a suitable control 18 for gating or passing a preselected number of pulses 21 (FIG. 2). These pulses 21, suitably shaped and amplified, are directed onto the surface 22 of a target 24 for generating a plasma 26 of neon-like ions in a cylindrical cloud adjacent to the target surface. Target 24 is positioned between a pair of opposed coaxial X-ray mirrors 28, 30 at fixed spacing ct equal to the inter-pulse time interval t multiplied by speed of light c. The axis of mirrors 28, 30 is spaced from target surface 22 at a position to be approximately coaxial with plasma 26. Amplified light pulses 21 thus produce spontaneous X-ray emissions within plasma 26 along the axis of mirrors 28, 30 during each pulse of the train. Mirrors 28, 30 and target plasma 26 thus form a multi-pass oscillator cavity 32.

With target 24 positioned within cavity 32 formed by mirrors 28, 30, whose length is exactly equal to the inter-pulse interval, the X-ray lasing emission generating during each radiation pulse is synchronized to oscillations within the lasing cavity, so that the oscillating lasing energy gets boosted or amplified during each passage through the plasma. At least one of the mirrors

30 is partially transmissive for extracting output energy. The following equation relates intensity gain ratio of output laser energy to the other parameters of cavity 32:

$$\frac{In}{Io} = \sum_{i=1}^{n} T(Re^{aL})^{i-1}$$

where Io equals intensity of X-ray emission at plasma 26 responsive to each pulse 21, R is reflectivity of mirrors 28, 30, T is mirror transmissivity, a is a gain co-efficient, and L is length of the plasma gain medium along the axis of mirrors 28, 30. As shown in FIG. 4, for a mirror reflectivity R equal to thirty percent and a transmissivity T equal thirty percent, and a gain-length product aL equal to two, intensity increase for n equal to ten passes is approximately 1,000. For a gain-length product aL equal to three, the intensity increase for ten passes is over 10^6.

FIG. 3 illustrates a modified embodiment of the invention wherein the cavity 32 is formed by a pair of spherical mirrors 28, 30 that are axially opposed to and aligned with each other, and are confocal adjacent to the surface 22 of target 24 positioned midway therebetween. Spherical reflectors 28, 30 help control cavity energy upon occurrence of density gradients within plasma 26. Output extraction is accomplished by forming mirror 30 as a grating that reflects zero-order X-ray radiation toward the opposing mirror 28, while reflecting one of the higher orders of radiation out of the cavity a intensity In. FIG 5 illustrates another embodiment of the invention in which mirror 30 is provided with a multiplicity of small holes through which a portion of the X-ray energy passes to a reflector 36, while the remainder is reflected through plasma 26 to mirror 28. Energy incident on mirror 36 is reflected onto a mirror 38, and thence onto a detector 40.

Target 24 may be of any suitable construction that will generate and sustain a plasma 26 between mirror 28, 30. Solid targets are appropriate because the plasma formed by each light pulse is reproducible in space and time. A slot-orifice gas jet target is also suitable. The following table illustrates, for various target materials (Z), and exemplary lasing and output parameters:

Z	Lasing (λA)	Intensity (W/cm^2)	Plasma Length (mm)	Energy (joules)	Pulse Length (ps)	No. of Pulses
C	182	5×10^{12}	10	6	100	83
F	81	2×10^{13}	10	20	20	25
Na	54	3×10^{13}	10	36	20	13
Mg	45	4×10^{13}	10	48	20	10
Al	39	5×10^{13}	10	60	20	8
Se	209 206	5×10^{13}	5	120	450	4

The invention claimed is:

1. An X-ray laser amplifier that includes: means for providing a series of high-power light pulses at uniform temporal spacing, and an X-ray laser cavity including a pair of reflective means spaced from each other by a distance that corresponds to temporal spacing between said light pulses and a target positioned to be illuminated by said light pulses between said reflective means, said target being of a character and structure to from a plasma of ions in response to illumination by said light pulses for spontaneous emission of X-ray radiation between said reflective means, such that amplitude of

X-ray emissions from said plasma is boosted upon each passage through said plasma, at least one of said reflective means being constructed for extraction of amplified X-ray energy from said cavity.

2. The amplifier set forth in claim 1 wherein said reflective means comprises spherical mirrors.

3. The amplifier set forth in claim 2 wherein said target is positioned mid-way between said mirrors, said mirrors being confocal at said target.

4. The amplifier set forth in claim 3 wherein said at least one reflective means comprises a spherical mirror/grating for reflecting zero-order radiation toward the other mirror within said cavity and reflecting a higher order radiation out of said cavity.

5. The amplifier set forth in claim 1 wherein said at least one reflective means comprises a partially transparent mirror.

6. The amplifier set forth in claim 1 wherein said pulse-providing means comprises a mode-locked laser.

7. An X-ray laser that comprises a target and means for directing high-power laser radiation onto said target to form a plasma of ions at a density and temperature for spontaneous emission of X-ray energy along an axis at predetermined orientation with respect to said target,

characterized in that said radiation-directing means comprises means for directing a series of high-power laser pulses onto said target at predetermined constant temporal spacing, and

in that said laser further includes a pair of reflective means positioned on opposite sides of said target along said axis and forming a cavity having a length corresponding to said temporal spacing, one of said reflective means being constructed for extraction of X-ray laser energy from said cavity.

8. The laser set forth in claim 7 wherein said radiation-directing means comprises a mode-locked laser for producing a continuing series of light pulses at said predetermined constant temporal spacing, and means for extracting a preselected number of said pulses and directing the same onto said target, said preselected number being coordinated with desired amplification of X-ray radiation.

9. The laser set forth in claim 8 wherein said reflective means comprises spherical mirrors, said target being positioned mid-way between said mirrors and said mirrors being confocal adjacent to said target.

10. The laser set forth in claim 9 wherein one of said mirrors comprises a spherical mirror/grating for reflecting zero-order radiation toward the other mirror within said cavity and reflecting a higher order of radiation out of said cavity.

11. The laser set forth in claim 8 wherein said at least one reflective means comprises a partially transparent mirror.

12. A method of generating high-power X-ray laser energy comprising the steps of:

(a) providing an X-ray laser cavity that includes a pair of opposed coaxial mirrors at predetermined fixed spacing and a target having a surface positioned between said mirrors,

(b) directing a series of light pulses onto said target surface at predetermined fixed time intervals and an intensity sufficient to form an ion plasma adjacent to said surface of a character and composition for spontaneous emission of X-ray energy along the axis of said cavity, said fixed spacing between said mirrors being equal to said time intervals multiplied by the velocity of light such that X-ray energy oscillating in said cavity is amplified upon each passage through said plasma, and

(c) extracting a portion of said X-ray energy oscillating in said cavity.

13. The amplifier set forth in claim 1 wherein said at least one reflective means comprises a mirror having a plurality of apertures positioned to transmit a portion of said X-ray energy through said apertures while reflecting the remainder of said energy toward the other said reflective means.

14. The laser set forth in claim 11 wherein said at least one reflective means comprises a mirror having a plurality of apertures positioned to transmit a portion of said X-ray energy through said apertures while reflecting the remainder of said energy toward the other said reflective means.

* * * * *

US005103452A

United States Patent [19]

London et al.

[11] Patent Number: 5,103,452

[45] Date of Patent: Apr. 7, 1992

[54] X-RAY LASER SYSTEM, X-RAY LASER AND METHOD

[75] Inventors: Richard A. London, Oakland; Mordecai D. Rosen, Berkeley, both of Calif.; Moshe Strauss, Omer, Israel

[73] Assignee: The United States of America as represented by the United States Department of Energy, Washington, D.C.

[21] Appl. No.: 647,075

[22] Filed: Jan. 29, 1991

[51] Int. Cl.[5] H01S 3/30

[52] U.S. Cl. 372/5; 372/1; 372/7; 372/39; 372/66

[58] Field of Search 372/5, 7, 1, 66, 39

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4,589,113	5/1986	Hagelstein	372/5
4,827,479	5/1989	Campbell et al.	372/5

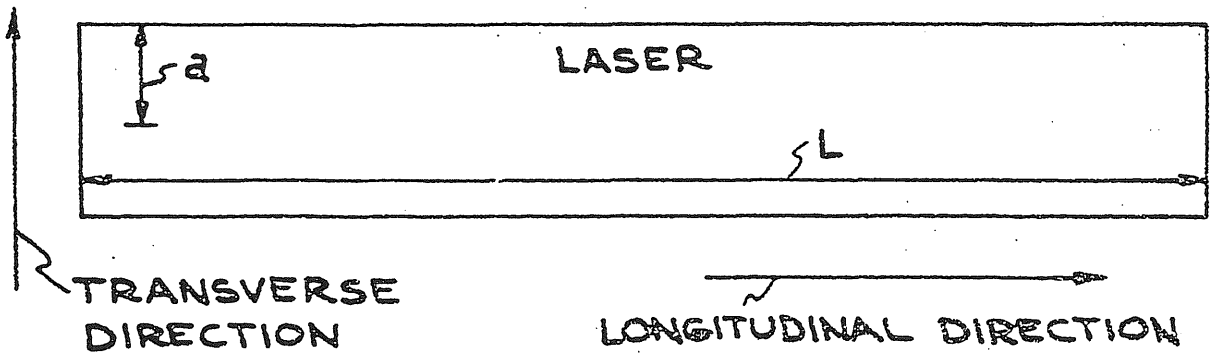
Primary Examiner—Georgia Epps

Attorney, Agent, or Firm—Henry P. Sartorio; Miguel A. Valdes; William R. Moser

[57] ABSTRACT

Disclosed is an x-ray laser system comprising a laser containing generating means for emitting short wave length radiation, and means external to said laser for energizing said generating means, wherein when the laser is in an operative mode emitting radiation, the radiation has a transverse coherence length to width ratio of from about 0.05 to 1. Also disclosed is a method of adjusting the parameters of the laser to achieve the desired coherence length to laser width ratio.

17 Claims, 1 Drawing Sheet



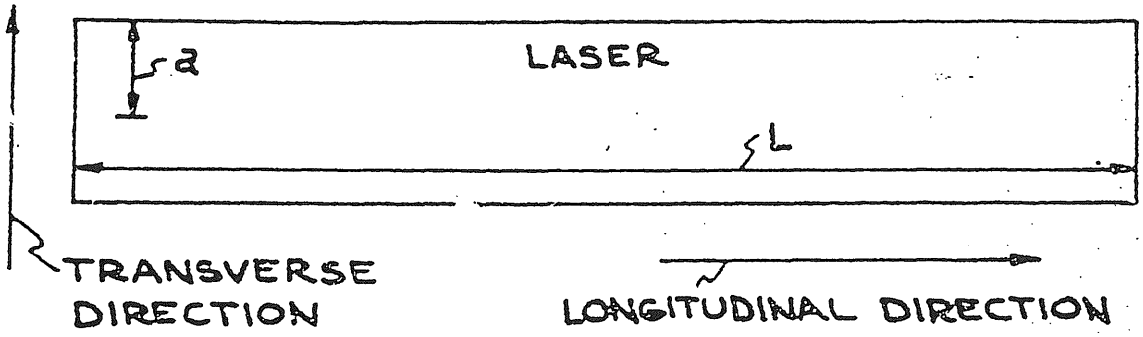


FIG. 1

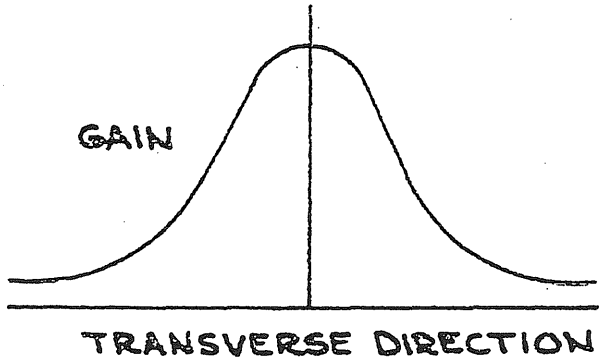


FIG. 2

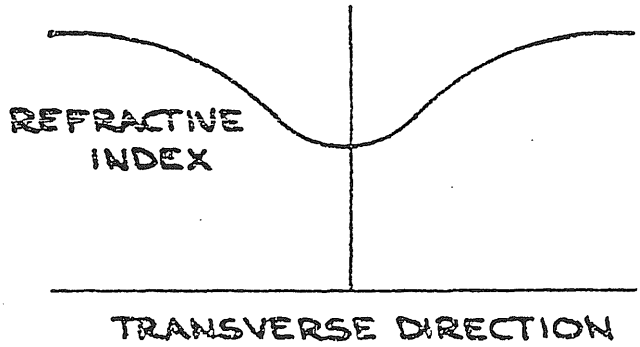


FIG. 3

X-RAY LASER SYSTEM, X-RAY LASER AND METHOD

The United States Government has rights in this invention pursuant to Contract No. W-7405-ENG-48 between the United States Department of Energy and the University of California for the operation of Lawrence Livermore National Laboratory.

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to a laser system and laser having improved transverse coherence and to a method of achieving the improved coherence.

More particularly, it relates to an x-ray laser system and laser having improved transverse coherence which is suitable for use in obtaining improved x-ray holographic images.

X-ray laser systems and lasers have been known in the art since about 1984. X-ray lasers are similar to visible light lasers except that they generate x-rays when properly stimulated, or pumped, instead of conventional beams of light. The total "x-ray" region broadly covers 700 Å down to 0.1 Å wavelength. Traditionally, however, the x-ray range is considered to begin at about 300 Å. The x-ray region is further categorized as "soft" for wavelengths in the ~2-300 Å range and "hard" for shorter wavelengths. X-ray lasers can be used for a number of purposes, including the making of holographic images.

Laser irradiated exploding foils have recently been used to create soft x-ray lasers. When properly designed and irradiated, such foils give rise to elongated plasmas that have high density, nearly constant temperature and smooth transverse density profiles. Models for laser heated exploded foils, wires or fibers and spheres are described in a number of articles, including J. M. Dawson, Phys. Fluids 7, 981 (1964); W. J. Fader, Phys. Fluids 11, 2200 (1968); J. Dawson et al., Phys. Fluids, 12, 8757 (1969); R. E. Kidder, in Physics of High Energy Density (Academic, New York, 1971), p. 306; A. V. Farnsworth, Phys. Fluids 23, 1496 (1980), Rosen et al., Phys. Rev. Letters, 4,106 (1985), and R. A. London and M. D. Rosen, Phys. Fluids 29, 3813 (1986).

Discussions of the feasibility and ultimate utility of x-ray holography of biological samples are given by Solem et al., "Microholography of Living Organisms," Science, 218,229-2357 (1982), M. Howells, "Fundamentals Limits in X-ray Holography," in X-Ray Microscopy II, D. Sayre et al., Eds, (Springer Verlag, New York, 1988) p. 263, and R. A. London, M. D. Rosen and J. E. Trebes, Appl. Optics, 28, 3397 (1989).

X-ray lasers which are to be used for holography, however, require highly coherent wave output. The degree of longitudinal coherence is generally adequate for holographic applications, but the transverse coherence of prior art lasers is generally inadequate to generate high resolution images. Coherence, as used herein, refers to the existence of a correlation between the phases of two or more waves, such as the reference wave and the object wave in the holographic process.

In a normal optical laser, coherence is achieved by operating the laser in a multi-pass cavity. Because the reflectivity of x-ray mirrors is low, (less than about 50%) and the duration of x-ray laser gain is short (of order 250 psec), x-ray lasers have been operated as single pass or few pass (up to three) devices. It has

therefore been difficult to design one with good transverse coherence.

Previous methods suggested for improving the transverse coherence involve using a lasing medium with a small cross-sectional area (see Rosen, Trebes and Matthews, "A Strategy for Achieving Spatially Coherent Output from Laboratory X-ray Lasers," Comments in Plasma Physics and Controlled Fusion, Vol. 10 p. 245, (1987)). The method suggested by Rosen et al., appears to be somewhat difficult to implement since it requires a two-component exploding foil—a lasant material surrounded by a non-lasant material, and furthermore, the lasant needs to be initially very thin (=80 Å in their example).

It would be desirable in the art to provide a laser and laser systems having improved transverse coherence, and a method of achieving improved coherence in an X-ray laser.

SUMMARY OF THE INVENTION

It is an object of this invention to provide an x-ray laser system containing an x-ray laser having improved transverse coherence in the wave output thereof.

It is a further object of this invention to provide an x-ray laser system containing an x-ray laser, the output of which has transverse coherence sufficient for it to be used to generate holographic images.

It is a still further object of this invention to provide a method of improving the transverse coherence of the output of an x-ray laser system and laser.

Other objects and advantages of the invention will be apparent from the description and drawings to follow

The objects of the invention are achieved by creating a x-ray laser system which utilizes a lasing medium having a specific class of transverse profiles of gain and/or refractive index. These profiles create gain-guiding and/or refractive anti-guiding, respectively, of the x-rays as they travel down the length of the laser and are amplified. The essential features of these profiles are that they be smooth and curved near the central axis of the laser, and that the gain is at a maximum on axis and the index of refraction is at a minimum on axis. Either gain-guiding or refractive index anti-guiding or a combination of the two effects can be used to create a coherent x-ray laser.

The laser system of this invention therefore comprises:

a. a laser containing generating means for emitting short wave length radiation, and

b. means external to said laser for pumping said generating means, wherein when in an operative mode emitting radiation, the radiation has a coherence length to width ratio of from about 0.5 to about 1.

In one aspect, the method of the invention is one for improving the transverse coherence of radiation being emitted from an x-ray laser system containing an x-ray laser which comprises: adjusting the design parameters of the laser so as to conform to the formula

$$a \leq 0.2(g\lambda)^{\frac{1}{2}}L$$

wherein all values are in cgs units, and a is equivalent to the full width half maximum of said laser, L is the length of said laser, g is equivalent to the maximum on axis value of the gain coefficient of said laser and λ is the wavelength of said laser.

In another aspect, the invention is a method of improving the transverse coherence of radiation being emitted from an x-ray laser which comprises: adjusting the design parameters of the laser so as to conform to the formula:

$$a \cong \eta(gL)^2/[\ln(4\eta)]^2$$

in which

$$\eta = \frac{N_e}{g}\ \frac{2e^2\lambda}{M_eC^2} = 6 \cdot 10^{-13}\frac{\lambda N_e}{g}$$

wherein all values are in cgs units, and a is equal to the full width half maximum of said laser, L is the length of said laser, g is the maximum on axis value of the gain coefficient, λ is the wavelength of said laser, N_e is the maximum on axis electron density, e is the electron charge, M_e is the electron mass and C is the speed of light.

In the foregoing, the first method described utilizes pure gain guiding to achieve improved transverse coherence; while the second method utilizes gain guiding and refractive index anti-guiding, wherein refraction is caused by transverse gradients in the election density.

In yet another aspect the invention comprises a method of improving the transverse coherence of radiation being emitted from an x-ray laser which comprises adjusting the design parameters of the laser so that the ratio of the coherence length to width of the laser ranges from about 0.05 to about 1.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic of X-ray laser showing transverse and longitudinal directions and width and length.

FIG. 2 is a graph of the gain profile of the x-ray laser used in the system of this invention.

FIG. 3 is a graph of the refractive index profile of the x-ray laser used in the system of this invention.

DETAILED DESCRIPTION OF THE INVENTION

For various applications, an x-ray laser may be required to have several of the following properties: high energy, high power, efficiency, short wavelength, short time duration, monochromaticity, and coherence. This invention provides a means to establish a high degree of transverse coherence of an x-ray laser can be substantially improved by adjustment of ... design parameters of the laser in accordance with certain mathematical formulas which have been developed and are described more fully below. While the invention, in general, may be applied to any x-ray laser, it is particularly adapted to a laser system containing an exploding foil x-ray laser such as is described in articles by M. D. Rosen et al. entitled "Exploding Foil Technique for Achieving a soft X-ray Laser", Phys. Rev. Lett., 54, 106 (1985), R. A. London and M. D. Rosen, entitled "Hydrodynamics of Exploding Foil X-Ray Lasers," appearing in Phys. Fluids 29:(11), November 1986, pp. 3813-3822, and U.S. Pat. No. 4,827,479, all three of which are incorporated herein by reference.

A representative laser system comprises a selenium foil approximately 750 Å thick, attached to a formvar substrate approximately 1500 Å thick. This embodiment has employed two pulsed beams of line focused, optical laser radiation each having an energy flux of approximately 5×10^{13} watts/cm^2, a wavelength of approximately 0.532 microns, and a full width at half maximum amplitude duration of approximately 450 picoseconds to pump the selenium foil. The line focused beams each illuminated generally rectangular portions of the selenium and formvar target that are approximately 1.1 cm long and approximately 0.02 cm wide.

Coherence is a property of light that determines how well light can be focused and how well interference experiments and measurements based on interference can be performed. Introductions to optical coherence may be found in several text books. There are two types of coherence: longitudinal (or temporal) and transverse (or spatial). Longitudinal coherence characterizes how well the phase of a wave is maintained over a distance in the propagation direction, while transverse coherence describes how the phase is maintained in the perpendicular direction.

The coherence requirements for x-ray holography using a 45 Å x-ray laser require the longitudinal coherence length to be larger than the path length difference between the object beam and the reference beam, estimated to be about 5 μm in a Fourier-transform holography system. The longitudinal coherence length is related to the line width by $L_l = \lambda^2/\Delta\lambda$, where λ is the laser wavelength. Using the thermal Doppler width for an estimate, we get $L_l = 37$ μm. This estimate is supported by the observation of a sub-Doppler line profile of a neon-like selenium laser at 206 Å. The longitudinal coherence is therefore thought not to be a problem. The situation is more difficult for transverse coherence. The transverse coherence length must be larger than the extent of the sample, typically $\simeq 10$ μm, and a certain amount of energy must irradiate the sample to provide high signal-to-noise hologram. The desired coherence length is obtainable by using a pinhole in front of the laser or by placing the object far from the laser, however, the combined requirement of high energy and coherence is the difficulty, requiring efficient production of coherent radiation. The required coherent energy is estimated to range from 1 to 17 μJ for a 750- to 300 Å resolution hologram of a gold tagged sample and 1000 μJ for a 300 Å resolution hologram of an untagged sample of protein in water. An improvement in the coherence of the current lasers is called for to meet the transverse coherence requirements.

In mirrorless lasers, such as most x-ray lasers, a high degree of transverse coherence is more difficult to achieve than for usual lasers containing cavities with highly reflective mirrors. Transverse coherence is a property of a laser which describes how well correlated the output radiation is at various transverse (i.e. perpendicular to the laser beam) positions in the beam. If the radiation is well correlated, the electromagnetic wavefront will be smooth. A high degree of transverse coherence is a property which allows one to combine different parts of the beam (e.g. by passing the radiation through interference slits) and obtain a steady, high contrast interference pattern. It is thus very important for applications, such as holography, which rely on wave interference in order to make images, or other measurements. We utilize the concept of a transverse coherence length to describe the property of transverse coherence. The transverse coherence length is the distance over which a good correlation is maintained. For a beam of low or poor coherence, the transverse coherence length is small, while for a beam of high coherence, the transverse coherence length is large. The

fraction of the width of the laser over which good correlation in the output is maintained is called the relative coherence length. The relative coherence length is defined, in other words, as the ratio of the transverse coherence length to the width of the laser. It describes the portion of a laser beam which is usable for interference experiments, such as holography. The greater the relative coherence length, the greater is the fraction of output radiation which is coherent and which is therefore usable for applications requiring coherence. It is the object of this invention to make the relative coherence length large—as close to unity as possible. We thus define good coherence for a laser as the property of having a large value of the relative coherence length (greater than 0.05, ideally approaching 1).

Previous methods to improve the coherence of x-ray lasers rely on making the laser very long and narrow (M. D. Rosen et al., "Strategy for Achieving Spatially Coherent Output from Laboratory X-Ray Lasers," Comments in Plasma Physics and Controlled Fusion, Vol. 10, p. 245, (1987)). In a simple incoherent disk source model of an x-ray laser having constant gain and no refraction, (London et al., "Coherent X-ray Lasers for Applications," Lawrence Livermore National Laboratory Report, UCRL-JC-105731, to appear in Proceedings at 2nd International Colloquium on X-Ray Lasers, (1990), eds. G. J. Pert and G. J. Tallents (IOP: Bristol UK)), the relative coherence length is given approximately by $1/F$, where F is a parameter of the laser known as the Fresnel number, $F=2\pi a^2/\lambda L$). Here a is the half-width of the laser, L is its length and λ is the wavelength. This explains the design criterion for a long narrow laser, i.e. to make the relative coherence length near one we need F near one. For example, Rosen, Trebes, and Mathews (1987) suggest a laser of 0.0025 cm wide by 3 cm long, operating with a lasant of neon-like selenium ions at 206 Å and 210 Å. Such a narrow configuration is hard to achieve. The implementation suggested by Rosen, Trebes, and Mathews (1987) uses an exploding foil in which the lasant material is surrounded by a different material (ytterbium in this case). Furthermore, the simple theory leading to this design only applies to the particular case when the gain coefficient is constant within the laser and when there is no refraction within the laser. This is not generally the case for x-ray lasers created by exploding foils. Here we expect gradients in both the gain and the electron density (which gives rise to refraction in a plasma).

We have invented another method to achieve good transverse coherence. This invention came from considering the effects of transverse variations in the gain coefficient and in the refractive index (caused by electron density in a plasma), and by considering a detailed model for calculating the expected degree of coherence of a laser, more accurate than the simple incoherent disk model described above. Our technique for creating a coherent x-ray laser utilizes a lasing medium having a specific class of transverse profiles of gain and/or refractive index. These profiles create gain-guiding and/or refractive anti-guiding, respectively, of the x-rays as they travel down the length of the laser and are amplified. The essential features of these profiles are that they be smooth and rounded near the central axis of the laser, and that the gain has a maximum on axis and the index of refraction has a minimum on axis. Either gain-guiding or index anti-guiding or a combination of the two effects can be used to create a coherent x-ray laser. The creation of smooth rounded profiles is a natural consequence of using an exploding foil to create the lasers. That is, the natural state of density of matter in an exploding foil assumes a smooth, rounded (bell-shaped distribution) during the time when x-ray lasing takes place, during the history of an exploding foil (R. A. London et al., "Hydrodynamics of Exploding Foil X-Ray Lasers," Physics of Fluids, Vol. 29, p. 3813, (1986)).

The analysis of the relative coherence length of a rounded-profile x-ray laser, and the derivation of the design parameters for a high coherence laser are described in the paper entitled "Modal Analysis of X-Ray Laser Coherence" by London, Strauss and Rosen appearing in Physical Review Letters, 65, pp. 563-566 (July 30, 1990) which is incorporated herein by reference. We summarize the material in that paper which is relevant to this invention.

The coherence is described by absolute value of the complex degree of coherence, labelled as $|\mu|$. This function describes the degree of correlation between the electric field of the laser radiation at two separate transverse positions. The complex degree of coherence generally drops from a value of one when the two points are very close together to zero as the points are moved further apart. The place where $|\mu|$ drops to $\frac{1}{2}$ is defined as the transverse coherence length, for the purposes of this invention. The ratio of the transverse coherence length to the width of the laser, which we define as the relative coherence length, describes how coherent the total output of the laser is. It is desirable to have a laser in which this ratio is as close to one as possible, in order that the radiation emanating from the laser is a coherent as possible. In practice, we consider ratios of 0.05–0.1 sufficient, 0.1–0.5 good and 0.5–1.0 very good transverse coherence.

The calculation of the complex degree of coherence and the relative coherence length is accomplished by a modal analysis of the electromagnetic wave equation. The paraxial approximation is first made to the wave equation. Then a specific mode expansion is assumed for the electric field which is to be a solution of the wave equation. On substituting this mode expansion into the equation one gets two equations, a transverse eigenvalue-eigenfunction equation, and a longitudinal amplification equation. Given a set of functions which satisfy the transverse mode equation for given transverse profiles of gain and refractive index, which we call modes, the longitudinal equation is solved for the output radiation quantities, such as the intensity of radiation and the complex degree of coherence (intensity and coherence). The output properties (intensity and coherence) are in the form of a double sum over transverse mode products, each term having a transverse factor and a longitudinal (amplification) factor.

This modal analysis has been applied both to a square profile lasers having constant gain coefficient and index of refraction in a finite region, and to smooth profile lasers. In the case of smooth profiles both parabolic functions and functions of the form $\cosh^{-2}(x/a)$, where x is the transverse coordinate direction and a is the approximate width of the laser have been studied. For the case of square profile lasers with no refraction, the results predicted by the simple incoherent disk model discussed above are reproduced by this more exact analysis. That is, the coherence length scales inversely as the Fresnel number. For the case of the smooth rounded profiles (i.e. parabolic and $\cosh^{-2}$ profiles) it is found that good coherence can be achieved by requir-

ing that the output radiation intensity and the complex degree of coherence be dominated by one or a few of the first (low mode) terms in the double sum over the modes. For the cases of very weak refraction and very strong refraction compared to gain, the following scaling laws describe the parameters necessary to achieve a high degree of transverse coherence.

For pure gain guiding, the equation is:

$$a \leq 0.2(g\lambda)^{\frac{1}{2}}L$$

For strong refractive anti-guiding, with refraction due to plasma electrons, the equation is

$$a \geq \pi(gL)^2/[\ln(\eta)]^{\frac{1}{2}}$$

in which

$$\eta = \frac{N_e}{g}\,\frac{2e^2\lambda}{M_e c^2} = 6 \times 10^{-13}\frac{\lambda N_e}{g}.$$

where e is the electron charge,
where all quantities are in cgs units, and
a = full width half maximum of the laser, i.e., gain and density
L = length of the laser
g = maximum on-axis value of the gain coefficient of laser
λ = wavelength of the laser
N_e = maximum on-axis electron density
e = electron charge (constant)
M_e = electron mass (constant)
C = speed of light (constant)

A schematic diagram of such a laser configuration is shown in FIGS. 1-3. FIG. 1 is a schematic diagram of a laser. FIG. 2 is a graph illustrating the optimum gain profile for the laser, while FIG. 3 is a graph illustrating the optimum refractive index. The mechanism by which such profiles improve the coherence is by reducing the cross-sectional area of the region of the laser in which significant amplification occurs. This results from the fact that gain guiding and the index anti-guiding favor the amplification of radiation which travels straight down the center of the laser. Gain guiding implies that the x-rays which travel down the middle of the laser experience more amplification because that is where the gain is maximum. Other x-ray paths will not experience as much amplification because they do not stay in the region of the maximum (on-axis) gain. Refractive anti-guiding aids this effect [illegible] rays traveling straight down the middle of the lase[illegible] remain in a region of nearly flat refractive index and therefore travel relatively straight. Rays which travel in some other direction bend out of the lasing medium.

One way to make the appropriate transverse profiles is to use an exploding foil plasma x-ray laser. In such a laser, the density of both ions and electrons have their maximum values on the axis and they drop off to either side. They have smooth rounded profiles, which can be described by Gaussian functions (London and Rosen 1986). Since the main determinant of gain is the ion density, the gain can have the desired on-axis peak. The refraction in a plasma is dominated by the effect of the free electrons and decreases with increasing electron density. Thus, the natural electron density profile in an exploding foil x-ray laser has the desired property of a minimum in index of refraction on axis. The particular values of the laser parameters which determine the coherence, such as g, N_e, and a and L, can be set by varying the initial width and length of the exploding foil and the intensity and pulse duration of the optical laser beams which energize the foil as described in the paper by London and Rosen (1986).

This invention will be more fully understood with reference to the following examples, which are intended to be illustrative of the invention but not limiting thereof.

EXAMPLE 1

A. 206 Å neon-like selenium exploding foil laser of the type previously described is designed which uses neon-like selenium ions as the lasant. It gives rise to strong lasing at $\lambda = 206$ Å and $\lambda = 210$ Å and weaker lasing at other wavelengths. The plasma conditions at the peak lasing time are:
$a = 8.5 \times 10^{-3}$ cm
$g = 5$ cm^{-1}
L = 4 cm or larger
$N_e = 3.5 \times 10^{20}$ cm^{-3}

The gain is typical of values measured for neon-like selenium for thicker (large a) plasmas. The parameters a and N_e can be achieved by adjusting the initial thickness of the foil, the irradiating optical laser intensity and the duration at the irradiating laser pulse.

The appropriate initial conditions to create the conditions for this laser may be estimated by using the model for the hydrodynamics of exploding foil x-ray lases described in the paper by London and Rosen (1986). Using this method, an approximate set of parameters have been determined. The foil consists of selenium on a plastic backing (e.g. Formvar or Lexan). The selenium has an area density of approximately 15 μg/cm^2, corresponding to a thickness of about 312 Å at density 4.8 gm/cm^3. The plastic has an areal mass density of approximately 5 μg/cm^2, corresponding to a thickness of approximately 500 Å at density 1 gm/cm^3. The foil is approximately 0.02 cm wide (or wider) by 4 cm long. The foil is irradiated by two opposing beams of 0.53 μm laser light. Each beam has a 200 psec (FWHM) duration and an energy of 250 J. The beams are focused to an area on the target approximately 0.01 cm by 4 cm in size.

EXAMPLE 2

A. 45 Å nickel-like tantalum laser is designed so that the parameters are:
$\lambda = 4.5 \times 10^{-7}$ cm
$a = 3.5 \times 10^{-3}$ cm
$g = 4.2$ cm^{-1}
L = 3 cm or larger
$N_e = 10^{21}$ cm^{-1}

A gain of 3 cm^{-1} has been measured for nickel-like tantalum. Somewhat higher gain (i.e. near 4.2 cm^{-1}) can be achieved by varying the target thickness, the irradiating laser intensity and the duration at the irradiating pulse.

The appropriate initial conditions to create the conditions for this laser are estimated by using the model for the hydrodynamics of exploding foil x-ray lasers described in the paper by London and Rosen (1986). The foil consists of tantalum on a plastic backing (e.g. Formvar or Lexan). The tantalum has an area density of approximately 20 μg/cm^2, corresponding to a thickness of about 120 Å at density 17 g/cm^3. The plastic has an areal mass density of approximately 5 μg/cm^2, corresponding to a thickness of approximately 500 Å at den-

sity 1 gm/cm^3. The foil is approximately 0.02 cm wide (or wider) by 4 cm long. The foil is irradiated by two opposing beams of 0.53 μm laser light. Each beam has a 100 psec (FWHM) duration and an energy of 1250 J. The beams are focused to an area on the target approximately 0.01 cm by 4 cm in size.

In the preferred embodiment of the invention the ratio of coherence length to width can range from about 0.05 to 1, preferably from about 0.1 to 1, more preferably from about 0.5 to 1.

While specific embodiments of the invention have been illustrated, modifications and changes of the apparatus, parameters, etc. will become apparent to those skilled in the art, and it is intended to cover in the appended claims all such modifications and changes which come within the scope of the invention.

We claim:

1. An x-ray laser system comprising an x-ray laser capable of emitting radiation in the range of 10 eV to 10 KeV, such that the emitted radiation is in the x-ray range of the electromagnetic spectrum, and whose emitted radiation has a ratio of transverse coherence length to the width of said laser in identical units of measure ranging from about 0.05 to 1.

2. An x-ray laser system comprising a source of x-ray radiation and means for energizing said source, wherein emitted radiation from said source has a ratio of transverse coherence length to the width of said source in identical units of measure ranging from about 0.05 to 1.

3. An x-ray laser system comprising:

a. a laser having a transverse gain profile in which the gain has a given on-axis value containing generating means for emitting short wave length coherent radiation, and

b. means external to said laser for energizing said generating means, wherein when emitting radiation, the ratio of the transverse coherence length of said radiation to the width of said laser in identical units of measure, ranges from about 0.05 to 1.

4. The system of claim 3, wherein said generating means is an exploding thin foil, heated to a temperature sufficient to excite electrons in the atoms thereof and thereby emit short wavelength radiation.

5. The system of claim 3, wherein said means for energizing said generating means is a pulsed neodymium-glass laser.

6. The system of claim 3, wherein the transverse gain profile of the radiation emitted from said generating means has a parabolic configuration.

7. The system of claim 6, wherein the physical parameters of said laser are determined in accordance with the formula:

$$a \lesssim 0.2\,(g\,\lambda)^{\frac{1}{2}}L$$

wherein all values are in cgs units, and a is equivalent to the full width half maximum width of said laser, L is the length of said laser, g is equivalent to the on-axis value of the gain coefficient of said laser, and λ is the wavelength of said laser.

8. An x-ray laser system comprising:

a. an exploding foil laser capable of emitting radiation in the x-ray range, and

b. means external to said exploding foil laser for energizing it comprising:

a pulsed neodymium-glass laser,

wherein, the radiation emitted from said exploding foil laser, when heated to a temperature sufficiently high to emit radiation in the x-ray range, has a ratio of transverse coherence length to width of said laser in identical units of measure ranging from about 0.05 to 1.

9. An x-ray laser system comprising:

a. a laser capable of emitting radiation in the range of 10 eV to 10 KeV, such that the emitted radiation is in x-ray range of the electromagnetic spectrum.

b. means external to said laser for energizing said laser to cause emission of radiation therefrom, wherein when energized said radiation emitted therefrom has a ratio of transverse coherence length to width of said laser in identical units of measure ranging from about 0.05 to 1.

10. A method of improving the transverse coherence of radiation being emitted from an x-ray laser having a transverse gain profile in which the gain has a given on-axis value which comprises: adjusting at least one of the length, width or gain for a given wavelength of said laser so as to conform to the formula

$$a \lesssim 0.2\,(g\,\lambda)^{\frac{1}{2}}L$$

wherein all values are in cgs units, and a is equivalent to the full width half maximum width of said laser, L is the length of said laser, g is equivalent to the maximum on-axis value of the gain coefficient of said laser, and λ is the wavelength of said laser.

11. A method of improving the transverse coherence of radiation being emitted from an x-ray laser having a transverse gain profile in which the gain has a given on-axis value which comprises: adjusting the physical design parameters of said laser including at least one of the length, width, gain or electron density for a given wavelength so as to conform to the formula:

$$a \cong \eta(gL)^2/[\ln(4\eta)]^{\frac{1}{2}}$$

in which

$$\eta = \frac{N_e}{g}\,\frac{2e^2\lambda}{M_e C^2} = 6 \times 10^{-13}\,\frac{\lambda N_e}{g}$$

where all values are in cgs units, and a is equal to the full width half maximum of said laser, L is the length of said laser, g is the maximum width on axis value of the gain coefficient of said laser, λ is the wavelength of said laser, N_e is the maximum on-axis electron density, e is the electron charge, M_e is the electron mass and C is the speed of light.

12. The method of claim 10, wherein said laser is an exploding foil laser.

13. The method of claim 12, wherein the foil of said exploding foil laser is tantalum.

14. The method of claim 12, wherein the foil of said exploding foil laser is selenium.

15. The method of claim 11, wherein said laser is an exploding foil laser.

16. The method of claim 15, wherein the foil of said exploding foil laser is tantalum.

17. The method of claim 15, wherein the foil of said exploding foil laser is selenium.

* * * * *

US005117432A

United States Patent [19]

Nilsen

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[45] Date of Patent: May 26, 1992

[54] VANADIUM-PUMPED TITANIUM X-RAY LASER

[75] Inventor: Joseph Nilsen, Livermore, Calif.

[73] Assignee: The United States of America as represented by the United States Department of Energy, Washington, D.C.

[21] Appl. No.: 654,457

[22] Filed: Feb. 13, 1991

[51] Int. Cl.[5] H01S 3/30

[52] U.S. Cl. 372/5; 372/7; 372/39; 372/70

[58] Field of Search 372/5, 7, 39, 66, 70

[56] References Cited

U.S. PATENT DOCUMENTS

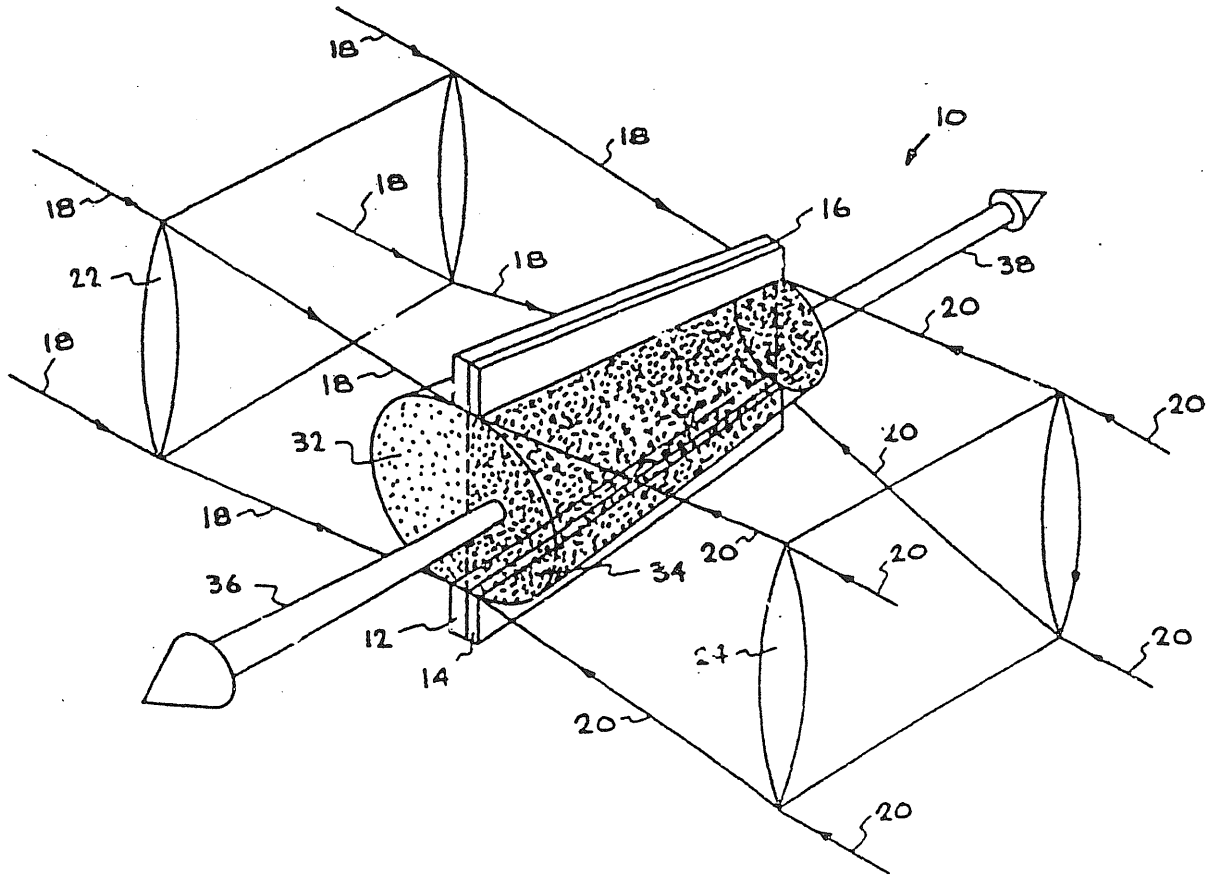
4,731,786	3/1988	MacGowan et al.	372/5
4,827,479	5/1989	Campbell et al.	372/5
4,977,572	12/1990	Nilsen	372/5
5,003,544	3/1991	Nilsen	372/5

Primary Examiner—William L. Sikes
Assistant Examiner—Robert E. Wise
Attorney, Agent, or Firm—Miguel A. Valdes; Roger S. Gaither; William R. Moser

[57] ABSTRACT

A resonantly photo-pumped x-ray laser (10) is formed of a vanadium (12) and titanium (14) foil combination (16) that is driven by two beams (18, 20) of intense line focused (22, 24) optical laser radiation. Ground state neon-like titanium ions (34) are resonantly photo-pumped by line emission from fluorine-like vanadium ions (32).

10 Claims, 4 Drawing Sheets



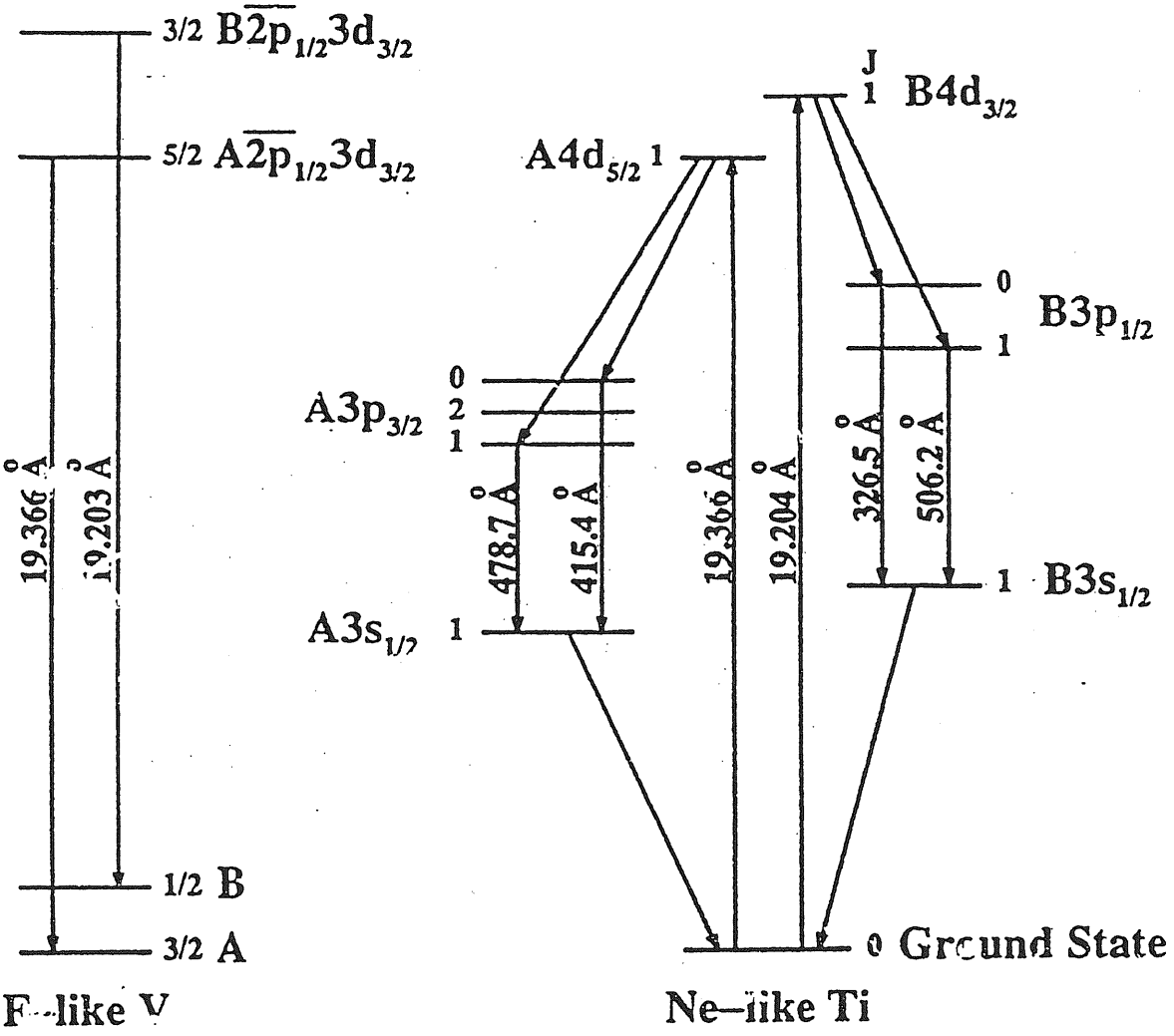

3/2 B2p1/2 3d3/2
5/2 A2p1/2 3d3/2
19.366 Å
19.203 Å
1/2 B
3/2 A
F-like V
J
i
B4d3/2
A4d5/2 1
0
B3p1/2
1
A3p3/2
0
2
1
478.7 Å
415.4 Å
19.366 Å
19.204 Å
326.5 Å
506.2 Å
A3s1/2 1
1 B3s1/2
0 Ground State
Ne-like Ti

FIG. 1A

Table 1. Laser transitions, wavelengths, and gains for Ne-like Ti				
Transition	Wavelength(Å)	Gain(cm^{-1}) for n_λ = 0.005	0.010	0.020
$\overline{2p_{1/2}}\ 3p_{1/2}\ (J=0) \rightarrow \overline{2p_{1/2}}\ 3s_{1/2}\ (J=1)$	326.5	2.90	6.81	9.91
$\overline{2p_{1/2}}\ 3p_{3/2}\ (J=2) \rightarrow \overline{2p_{1/2}}\ 3s_{1/2}\ (J=1)$	472.1		0.56	2.18
$\overline{2p_{1/2}}\ 3p_{3/2}\ (J=1) \rightarrow \overline{2p_{1/2}}\ 3s_{1/2}\ (J=1)$	473.2	2.10	5.45	8.78
$\overline{2p_{1/2}}\ 3p_{1/2}\ (J=1) \rightarrow \overline{2p_{1/2}}\ 3s_{1/2}\ (J=1)$	506.2	2.90	7.44	11.88
$\overline{2p_{3/2}}\ 3p_{3/2}\ (J=0) \rightarrow \overline{2p_{1/2}}\ 3s_{1/2}\ (J=1)$	508.8	1.26	2.92	4.13
$\overline{2p_{1/2}}\ 3p_{1/2}\ (J=0) \rightarrow \overline{2p_{3/2}}\ 3s_{1/2}\ (J=1)$	285.1	1.35	3.14	4.48
$\overline{2p_{3/2}}\ 3p_{3/2}\ (J=0) \rightarrow \overline{2p_{3/2}}\ 3s_{1/2}\ (J=1)$	415.4	2.99	6.83	9.43
$\overline{2p_{3/2}}\ 3p_{3/2}\ (J=2) \rightarrow \overline{2p_{3/2}}\ 3s_{1/2}\ (J=1)$	459.4	0.56	2.13	4.33
$\overline{2p_{3/2}}\ 3p_{3/2}\ (J=1) \rightarrow \overline{2p_{3/2}}\ 3s_{1/2}\ (J=1)$	478.7	3.19	8.38	13.09
$\overline{2p_{3/2}}\ 3p_{1/2}\ (J=2) \rightarrow \overline{2p_{3/2}}\ 3s_{1/2}\ (J=1)$	507.6	1.30	4.15	7.75

FIG. 1B

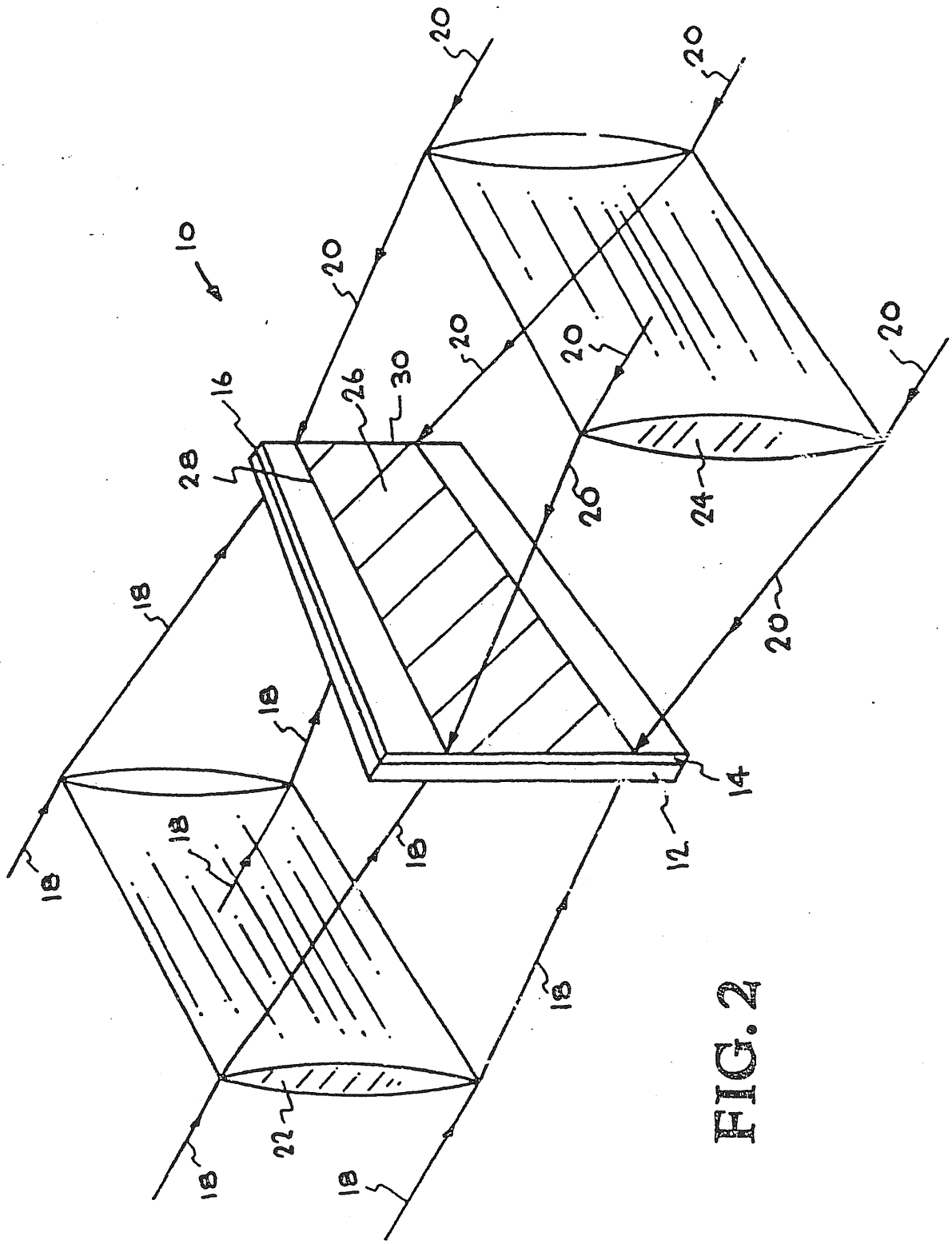


FIG. 2

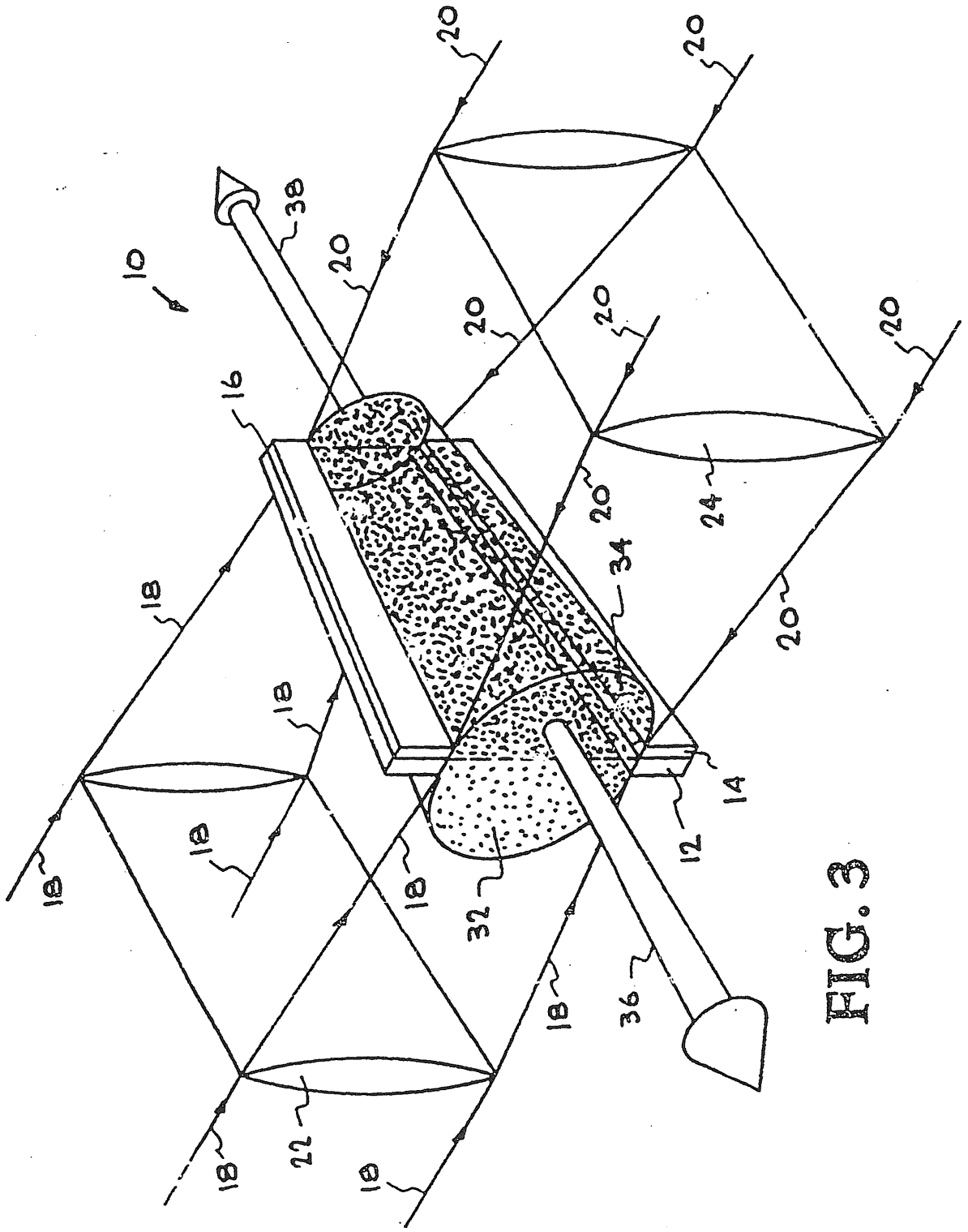


FIG. 3

VANADIUM-PUMPED TITANIUM X-RAY LASER

The U.S. Government has rights to this invention pursuant to Contract No. W-7405-ENG-48 between the U.S. Department of Energy and the University of California, for the operation of Lawrence Livermore National Laboratory.

BACKGROUND OF THE INVENTION

The invention described herein relates generally to x-ray lasers and more particularly to resonantly photo-pumped x-ray lasers.

The first operational laboratory x-ray laser, which used collisional excitation as the pumping mechanism, was taught by Campbell and Rosen in U.S. Pat. No. 4,827,479 issued May 2, 1989. Moreover, this x-ray laser is also described by Rosen et al. in Physical Review Letters 54, 106 (1985), with a discussion of the experimental demonstration of the laser provided by Matthews et al in Physical Review Letters 54, 110 (1985). This seminal work was also reported in Physics Today, March 1985, at pages 17 to 19. Additionally, a recent review of soft x-ray lasers is provided by Matthews and Rosen in Scientific American, December 1988, at pages 86 to 91.

The following are representative of the state-of-the-art in x-ray laser research and speculation: Cochran et al, in U.S. Pat. No. 4,803,687 issued Feb. 7, 1989, describe a sodium-neon laser target wherein Ne IX (He-like Ne) is resonantly photo-pumped by Na X (He-like Na). A carbon thermal buffer layer is required between the sodium and neon layers.

Hagelstein, in U.S. Pat. No. 4,660,203 issued Apr. 21, 1987, describes x-ray lasers wherein various multiply ionized species are used to pump high energy transitions in helium-like or hydrogen-like N, O, F, C or rare gases. For example, F-like Ti is indicated as a pump material at 24.907Å to drive a He-like N laser. The lasant material is located within a hollow container fabricated from parylene, or a material substantially transparent to radiation in the wavelength range from 60 to 300 Angstroms, and is multiply-ionized and undergoes at least one super-radiant laser transition.

Silfvast, in U.S. Pat. No. 4,592,064 issued May 27, 1986, discloses a scheme that permits high gain at visible and UV wavelengths in species such as Cd and Zn. A population inversion is established by producing a plasma that generates x-ray pulses in the 150 to 650 Angstrom (Å) wavelength range.

Elton, in U.S. Pat. No. 4,592,056 issued May 27, 1986, describes x-ray lasing systems wherein a neon-like sulfur plasma is used to pump a lithium-like neon plasma, and wherein a lithium-like silicon plasma is used to pump a lithium-like magnesium plasma.

Harris, in U.S. Pat. No. 4,380,072 issued Apr. 12, 1983, describes a method of exciting atoms to a storage level, then irradiating the excited atoms and thereby raising them to a higher level, whereupon the atoms lase to a lower level, other than ground, which is simultaneously emptied. This method results in the generation of XUV radiation.

Mani et al, in U.S. Pat. No. 4,229,708 issued Oct. 21, 1980, describe an x-ray laser wherein lithium-like atoms or ions are stimulated to lase by resonant or non-resonant antistokes Raman processes. The laser functions by directing filtered, black-body radiation in the soft x-ray region into a lithium-like vapor.

Jaegle et al, in U.S. Pat. No. 3,826,996 issued Jul. 30, 1974, describe obtaining a medium having a negative absorption coefficient within the ultra-violet and x-ray range, by focusing a giant-pulse laser beam on an aluminum target.

Despite tremendous progress in the development of x-ray lasers over the last several years, only two pumping mechanisms have been used to create gain and produce laser output. These have been collisional excitation, in the case of Ne-like and Ni-like lasers, and recombination, in the case of H-like and Li-like lasers.

Proposals have been made of many schemes using the resonant photo-pumping mechanism to drive various x-ray lasers; however, the resonant photo-pumping mechanism has not as yet been actually demonstrated in the x-ray, or even the soft x-ray, region. The shortest wavelength at which significant gain has been measured using resonant photo-pumping is 2163 Å in beryllium-like carbon pumped by a manganese plasma, in work reported by Qi and Krishnan, Phys. Rev. Lett. 59, 2051 (1987).

Nilsen, in U.S. Pat. No. 4,977,572 issued Dec. 11, 1990, describes a resonantly photo-pumped x-ray laser that enhances the gain of several laser lines that also lase because of collisional excitations and recombination processes. An aluminum and erbium foil combination is driven by two beams of intense line focused optical laser radiation. Ground state Ni-like Er ions are resonantly photo-pumped by line emission from H-like Al ions to produce 54–90 Å radiation.

Nilsen in U.S. patent application Ser. No. 07/420,433, filed Oct. 12, 1989, describes a resonantly photo-pumped x-ray laser in the 23–44 Angstrom range. A silicon and dysprosium foil combination is driven by two beams of intense line focused optical radiation. Ground state nickel-like dysprosium ions are resonantly photo-pumped by line emission from hydrogen-like silicon ions.

SUMMARY OF THE INVENTION

It is, therefore, an object of the invention to provide a resonantly photo-pumped x-ray laser.

Additional objects, advantages and novel features of the invention will be set forth in part in the description which follows, and in part will become apparent to those skilled in the art upon examination of the following or may be learned by practice of the invention. The objects and advantages of the invention may be realized and attained by means of the instrumentalities and combinations particularly pointed out in the appended claims.

To achieve the foregoing and other objects and in accordance with the purposes of the present invention, as embodied and broadly described herein, a resonantly photo-pumped x-ray laser is disclosed in which means are provided for producing a quantity of neon-like titanium ions in the ground state, together with means for resonantly photo-pumping two $2p \rightarrow 4d$ transitions in these ions to a pair of $4d$ levels, which decay directly to the $3p$ upper laser states of the laser, which lases on several $3p \rightarrow 3s$ transitions with wavelengths in the 280–510 Å range. The resonant photo-pumping is accomplished by a means that generates a quantity of fluorine-like vanadium ions in two $3d$ states, in spatial and temporal proximity to the neon-like titanium ions, with the resonant photo-pumping taking place on two $3d \rightarrow 2p$ emission lines from the fluorine-like vanadium ions.

In an embodiment of this invention, the x-ray laser comprises a vanadium foil upon which is deposited a titanium film, which together constitute a vanadium and titanium combination. The V foil is generally thicker than the Ti layer. Means are provided for simultaneously illuminating the vanadium and the titanium sides of the combination with beams of line focused, high power optical laser radiation. This driving illumination occurs over adjacent, long and thin and generally rectangular portions of the surfaces of the vanadium foil and titanium film combination. Preferably, the vanadium foil has a thickness in the approximate range from 100 to 5,000 Angstroms; and the titanium film has a thickness in the approximate range from 10 to 2000 Angstroms. Preferably, the two simultaneous, illuminating beams of driving optical laser radiation individually each have wavelengths within the approximate range from 0.25 to 11 microns; and temporal full widths at half maximum amplitude in the approximate range from 10 to 2000 picoseconds. Preferably, the beam that illuminates the vanadium side of the combination has a power density in the approximate range extending from 5×10^{12} to 5×10^{13} watts/cm^2, and the beam that illuminates the titanium side of the combination has a power density in the approximate range extending from 5633 10^{12} to 5×10^{13} watts/cm^2. Preferably, the adjacent, illuminated, generally rectangular portions of the vanadium and titanium combination, each have a length in the approximate range from 0.4 to 8.0 centimeters, and a width in the approximate range from 50 to 200 microns.

In a particular illustrative embodiment, optical laser pulses of about 0.5 micron wavelength, 600 ps pulsewidth, and intensity of 1×10^{13} W/cm^2 (on each side) are used. The Ti foil has a thickness of 20 Å, and the V foil thickness is 1000 Å. The illumination region has a length of 4.5 cm and a width of 120 microns.

The method for providing x-ray laser radiation of this invention, comprises the steps of providing a quantity of neon-like titanium ions in the ground state, and resonantly photo-pumping two $2p\rightarrow4d$ transitions of these ions to a pair of $4d$ levels, which decay directly to $3p$ upper laser states which lase on several $3p\rightarrow3s$ transitions. The resonantly photo-pumping step may be accomplished by generating a quantity of $3d$ state fluorine-like vanadium ions, in spatial and temporal proximity to the neon-like titanium ions, and resonantly photo-pumping on two $3d\rightarrow2p$ emission lines.

In another aspect of this invention, x-ray laser radiation may be provided by the single step of simultaneously illuminating the opposite sides of a combination comprised of a vanadium foil, upon which a titanium film has been deposited, with two driving beams of line focused, high power optical laser radiation, over adjacent, long and thin and generally rectangular portions of the vanadium and titanium sides of the combination.

The benefits and advantages of the present invention, as embodied and broadly described herein, include, inter alia, the provision of a novel resonantly photo-pumped x-ray laser.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated herein and form a part of the specification, illustrate an embodiment of the invention and, together with the description, serve to explain the principles of the invention. In the drawings:

FIG. 1A is the energy level diagram of the x-ray laser of this invention.

FIG. 1B is a table of laser transitions, wavelengths and gains for Ne-like Ti.

FIG. 2 is a schematic view of an x-ray laser in accordance with this invention, shown at an early time in its performance.

FIG. 3 is a schematic view of the x-ray laser of FIG. 2, shown at a later time in its performance, when vigorously producing x-ray laser radiation.

DETAILED DESCRIPTION OF THE INVENTION

The lasing scheme of the novel x-ray laser of this invention is shown in the energy level diagram of FIG. 1A. The laser uses a combination of titanium (Z=22) and vanadium (Z=23). The process comprises resonantly photo-pumping neon-like titanium (Ne-like Ti) ions in the ground state (J=0) to the $\overline{2p}_{3/2}4d_{5/2}$ (J=1) and $\overline{2p}_{\frac{1}{2}}4d_{3/2}$ (J=1) levels. This is accomplished using fluorine-like vanadium (F-like V) $\overline{2p}_{3/2}\overline{2p}_{\frac{1}{2}}3d_{3/2}$ (J=5/2) to $\overline{2p}_{3/2}$ (J=3/2) line emission at 19.366 Å, and $\overline{2p}_{\frac{1}{2}}\overline{2p}_{\frac{1}{2}}3d_{3/2}$ (J=3/2) to $\overline{2p}_{\frac{1}{2}}$ (J=½) line emission at 19.203 Å.

As shown in FIG. 1A, the basic lasing scheme consists of the F-like V $3d\rightarrow2p$ lines resonantly photo-pumping electrons in the ground state of the Ne-like Ti ions to the $\overline{2p}_{3/2}4d_{5/2}$ (J=1) and $\overline{2p}_{\frac{1}{2}}4d_{3/2}$ (J=1) levels. The bar over the $2p$ state indicates a hole or vacancy in the closed L shell [$1s^22s^22p^6$] or neon-like core. The notation A represents a $2p_{3/2}$ hole ($\overline{2p}_{3/2}$) in the neon-like core, while B represents a $2p_{\frac{1}{2}}$ hole ($\overline{2p}_{\frac{1}{2}}$). The value of the total angular momentum J is given next to each level. The $\overline{2p}_{\frac{1}{2}}4d_{3/2}$ (J=1) level decays preferentially to the $\overline{2p}_{\frac{1}{2}}3p_{\frac{1}{2}}$ (J=0) and $\overline{2p}_{\frac{1}{2}}3p_{\frac{1}{2}}$ (J=1) levels, which are the upper laser states. These upper laser levels lase to the $\overline{2p}_{\frac{1}{2}}3s_{\frac{1}{2}}$ (J=1) level, which is the lower laser level. The lower laser level decays back to the Ne-like ground state. The $\overline{2p}_{3/2}4d_{5/2}$ (J=1) level decays strongly to the $\overline{2p}_{3/2}3p_{3/2}$ (J=0) and $\overline{2p}_{3/2}3p_{3/2}$ (J=1) levels. These two levels lase to the $\overline{2p}_{3/2}3s_{\frac{1}{2}}$ (J=1) level. Other levels are also fed by the decay of the $4d$ levels and result in additional laser lines (not shown). All the laser transitions, along with the wavelengths and gains of the laser lines, are given in FIG. 1B.

Even in the absence of any fluorine-like vanadium pumping radiation, it is expected that some laser transition lines would be present in a neon-like titanium plasma, because of collisional excitation and recombination processes. However, the presence of fluorine-like vanadium pumping radiation is expected to significantly enhance the gain of each of the lines. On the other hand, some laser lines are only expected to exhibit gain when fluorine-like vanadium is present to photo-pump the neon-like titanium.

FIGS. 2 and 3 offer a schematic view of an x-ray laser 10, in accordance with this invention. X-ray laser 10 is the presently preferred embodiment of this invention, although it is believed that many different and highly beneficial embodiments of this invention may be realized in various situations and applications. X-ray laser 10 is shown at an early time in its performance in FIG. 2, and at a later time, when vigorously producing x-ray laser radiation, in FIG. 3. A consistent set of reference numerals is used in FIGS. 2 and 3. Since laser 10 is an x-ray laser, it utilizes no mirrors; therefore, amplification takes place on only a single pass through the sys-

tem. In this respect, x-ray laser 10 is typical of several previously known x-ray lasers.

X-ray laser 10 is comprised of a vanadium foil 12, that is flat and preferably has a thickness in the approximate range from 100 to 5000 Angstroms. A titanium film 14, flat and having a preferred thickness in the approximate range from 10 to 2000 Angstroms, is deposited upon, or attached to, vanadium foil 12, by techniques that are very well-known in the prior art. In some embodiments of this invention, vanadium foil 12 and titanium film 14 may each be attached to and supported by a very thin separating Plastic layer, not shown, comprised of, for example, mylar or parylene. This plastic layer may provide hydrodynamic isolation between the two foils. Vanadium foil 12 and titanium film 14 together provide a combination 16. The vanadium side of combination 16 is illuminated by a beam of line focused, high power optical laser radiation 18, while, simultaneously, the titanium side of combination 16 is illuminated by a beam of line focused, high power optical laser radiation 20, as shown. As schematically indicated, optical laser beams 18 and 20 are line focused by a pair of cylindrical lenses 22 and 24, respectively, by techniques that are very well known in the laser-related arts. Preferably, the two simultaneous beams of optical laser radiation 18 and 20 individually each have a wavelength or wavelengths in the approximate range from 0.25 to 11 microns, and a temporal full width at half maximum amplitude in the approximate range from 10 to 2000 picoseconds. Optical laser beam 18, that illuminates vanadium foil 12, preferably has a power density in the approximate range extending from 5×10^{12} to 5×10^{13} watts/cm^2, and optical laser beam 20, that illuminates titanium film 14, preferably has a power density in the approximate range extending from 5×10^{12} to 5×10^{13} watts/cm^2. Optical laser pulses having characteristics within these ranges are routinely provided by the Lawrence Livermore National Laboratory, located at Livermore, Calif. Optical laser beams 18 and 20 each illuminate an adjacent, long and thin and generally rectangular area on an opposite side of the vanadium and titanium combination 16. In particular, an area 26 on the titanium side of combination 16, is shown in FIG. 2 as illuminated by the optical laser beam 20. A similar area, not specifically shown, on the vanadium side of combination 16, is illuminated by optical laser beam 18. The area, or surface portion, 26 preferably has a length 28 in the approximate range from 0.4 to 8.0 centimeters, and a width 30 in the approximate range from 50 to 200 microns.

In a particular preferred embodiment, the optical pulses have a wavelength of about 0.5 microns, and a pulsewidth of 600 ps. The Ti foil has a thickness of 20 Å and the V foil is 1000 Å thick. The illumination region on the foils is 4.5 cm long and 120 microns wide. The illumination power density on each side of the foil combination is 1×10^{13} W/cm^2.

As shown in FIG. 3, the optical laser beams 18 and 20 energetically convert the portions of the combination upon which they impinge, into a vanadium plasma 32, and a titanium plasma 34. The titanium plasma 34 provides very many neon-like titanium ions in the ground state. The vanadium plasma 32, which is in spatial and temporal proximity to plasma 34, provides an abundant quantity of fluorine-like vanadium ions in the two $3d$ states, which vanadium ions emit a large amount of $3d$ to $2p$ line emission radiation at 19.366 Å and 19.203 Å, which radiation proceeds into plasma 34 and resonantly photo-pumps many of the neon-like titanium ions that are contained in the plasma 34, to the desired pair of $4d$ levels. The neon-like titanium ions, in the $4d$ levels, in plasma 34, proceed to provide, in accordance with the mechanisms particularly discussed above in reference to the energy level diagram of FIG. 1A, a pair of x-ray laser beams 36 and 38, schematically indicated, that comprise x-ray laser radiation.

A resonantly photo-pumped laser requires a good resonance between the lasant and a strong pump line which are in temporal and spatial proximity. Temporal and spatial proximity mean that the V and Ti ions are sufficiently close in space and time so that the pump energy can be absorbed by the lasant. The F-like V $\overline{2p_{3/2}}\overline{2p_{1/2}}3d_{3/2}$ $(J=5/2)\rightarrow\overline{2p_{3/2}}$ $(J=3/2)$ pump line is measured to be at 19.366 Å, while the F-like V $\overline{2p_{1/2}}\overline{2p_{1/2}}3d_{3/2}$ $(J=3/2)\rightarrow\overline{2p_{1/2}}$ $(J=\frac{1}{2})$ pump line is measured to be at 19.203 Å. The ground state to the $\overline{2p_{3/2}}4d_{5/2}$ $(J=1)$ transition in Ne-like Ti is measured to be at 19.366 Å, while the ground state to the $\overline{2p_{1/2}}4d_{3/2}$ $(J=1)$ transition is measured to be at 19.204 Å. Thus, good resonance exists.

The $3d\rightarrow2p$ lines of F-like V have sufficient pump strength to pump the Ne-like Ti ions. The table of FIG. 1B provides the gain of the various laser transitions for three different values of the pump strength, 0.005, 0.010, and 0.020 photons per mode. Ionization balance can be achieved between the V and Ti. Ne-like high Z plasmas have been made routinely in the laboratory. An advantage of the V-pumped Ti scheme is that the strong F-like V $3d\rightarrow2p$ lines have sufficient energy to photoionize Na-like Ti to Ne-like Ti, but they do not have enough energy to photoionize the ground state of Ne-like Ti to F-like Ti. This facilitates making a large population of Ne-like Ti without the fear of overionizing.

Low electron densities near 10^{18}/cc are required for the Ti lasant region to minimize collisional effects that tend to equilibrate the populations in the Ti lasing levels. Higher electron densities, near 10^{20}/cc,

and electron temperatures, between 100–300 eV, are required in the V plasma to produce the strong pump lines required. Therefore, the Ti will lase in the coronal region of the plasma and be pumped by the adjacent V region which is hotter and denser.

The gains achievable in Ne-like Ti by resonant photopumping were calculated assuming there were two strong F-like lines of equal strength available to pump the two Ne-like Ti $2p\rightarrow4d$ transitions, for several values of the pump line strength, 0.005, 0.010, and 0.020 photons per mode, for a 100μ thick pre-expanded foil of Ti at an initial ion density of 1.0×10^{19} ions/cc, an electron density determined by the ionization of the Ti, and initial ion and electron temperatures of 50 eV. The foil was then allowed to expand and cool while a constant pump strength for the F-like V lines was applied to the calculation. After 3.0 ns, the plasma region 300μ from the surface of the foil is at an electron temperature of 20 eV, a Ti ion density of 1.71×10^{17}/cc, and an electron density of 1.85×10^{18}/cc. Under these conditions 14% of the Ti ions are in the Ne-like ground state. FIG. 1B shows the gains of the Ne-like Ti laser lines under these plasma conditions. Five of the lines have gains greater than 5 cm^{-1} for a pump of 0.01 photons per mode, with the shortest wavelength of the five being at 326.5 Å. The gains of several lines are over 10 cm^{-1} at the higher pump strength. The lasing region is approximately 200μ thick.

To provide the low Ti ion densities for optimal pumping, a weak prepulse, e.g., a few nanoseconds before the

main optical pulse, can be applied. For example, optical beam 20 (and 18) can include a lower energy prepulse before the higher energy illumination pulse. The prepulse is of sufficient energy to produce a plasma in the ground state, while the higher energy pulse can excite the plasma to the higher states. The prepulse can be applied at the appropriate time so that the Ti plasma has spread spatially to produce the desired density when the higher excitation pulse is applied.

Instead of thin foils with double sided illumination, thick slab targets with single sided illumination could also be used. Ti and V plasmas in the above-described states will be formed so that resonant photo-pumping occurs.

It is thus appreciated that in accordance with the invention as herein described and shown in FIGS. 1 to 3, a novel resonantly photo-pumped x-ray laser is provided. The Ne-like Ti x-ray laser lases on several $3p \rightarrow 3s$ lines ranging from 280–510 Å based on resonant photo-pumping using radiation from two $3d \rightarrow 2p$ emission lines in F-like V.

The foregoing description of a preferred embodiment of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed, and obviously many modifications and variations are possible in light of the above teaching. The embodiment was chosen and described in order to best explain the principles of the invention and its practical application to thereby enable others skilled in the art to best utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the claims appended hereto

I claim:

1. An x-ray laser comprising:

means for providing a quantity of neon-like titanium ions in the J=0 ground state; and

means for resonantly photo-pumping the quantity of neon-like titanium ions from their J=0 ground state to the $\overline{2p}_{3/2}4d_{5/2}$ (J=1) and $\overline{2p}_{\frac{1}{2}}4d_{3/2}$ (J=1) levels, which decay directly to the upper laser states of the neon-like titanium.

2. An x-ray laser as recited in claim 1, wherein the means for resonantly photo-pumping the quantity of neon-like titanium ions comprises means for generating, in spatial and temporal proximity to the quantity of neon-like titanium ions, a quantity of fluorine-like vanadium ions in $\overline{2p}_{3/2}\overline{2p}_{\frac{1}{2}}3d_{3/2}$ (J=5/2) and $\overline{2p}_{\frac{1}{2}}\overline{2p}_{\frac{1}{2}}3d_{3/2}$ (J=3/2) states, which resonantly photo-pump on $\overline{2p}_{3/2}\overline{2p}_{\frac{1}{2}}3d_{3/2}$ (J=5/2)$\rightarrow\overline{2p}_{3/2}$ (J=3/2) and $\overline{2p}_{\frac{1}{2}}\overline{2p}_{\frac{1}{2}}3d_{3/2}$ (J=3/2)$\rightarrow\overline{2p}_{\frac{1}{2}}$ (J=$\frac{1}{2}$) emission lines.

3. An x-ray laser comprising:

a vanadium foil;

a titanium film deposited on the vanadium foil, to thereby provide a vanadium foil and titanium film combination; and

means for resonantly photo-pumping the titanium to upper laser states by simultaneously illuminating the opposite sides of said vanadium foil and titanium film combination with a first and a second beam of line focused, high power optical laser radiation, with the illumination occuring over adjacent, long and thin and generally rectangular portions of the vanadium and titanium combination

4. An x-ray laser as recited in claim 3, wherein the means for resonantly photo-pumping includes a prepulse of energy to produce a titanium plasma in the ground state.

5. An x-ray laser as recited in claim 3, wherein the vanadium foil has a thickness in the approximate range from 100 to 5000 Angstroms; wherein the titanium film has a thickness in the approximate range from 10 to 2000 Angstroms; wherein the first and second simultaneous beams of optical laser radiation individually each have a wavelength in the approximate range from 0.25 to 11 microns and a temporal full width at half maximum amplitude in the approximate range from 10 to 2000 picoseconds, with the beam that illuminates the vanadium side of the combination having a power density in the approximate range from 5×10^{12} to 5×10^{13} watts/cm^2, and with the beam that illuminates the titanium side of the combination having a power density in the approximate range from 5×10^{12} to 5×10^{13} watts/cm^2; and wherein the adjacent, generally rectangular illuminated portions of the vanadium and titanium combination, each have a length in the approximate range from 0.4 to 8.0 centimeters, and a width in the approximate range from 50 to 200 microns.

6. An x-ray laser as recited in claim 3, wherein the vanadium foil has a thickness of about 1000 Angstroms; wherein the titanium film has a thickness of about 20 Angstroms; wherein the first and second simultaneous beams of optical laser radiation have a wavelength of about 0.5 microns and a temporal full width at half maximum amplitude of about 600 picoseconds, with the beams that illuminate the vanadium and titanium sides of the combination each having a power density of about 1×10^{13} watts/cm^2; and wherein the adjacent, generally rectangular illuminated portions of the vanadium and titanium combination, each have a length of about 4.5 centimeters, and a width of about 120 microns.

7. A method for providing resonantly photo-pumped x-ray laser radiation, the method comprising the steps of:

providing a quantity of neon-like titanium ions in the J=0 ground state; and

resonantly photo-pumping the quantity of neon-like titanium ions from their J=0 ground state to the $\overline{2p}_{3/2}4d_{5/2}$ (J=1) and $\overline{2p}_{\frac{1}{2}}4d_{3/2}$ (J=1) levels, which decay directly to upper laser states of said neon-like titanium.

8. The method of claim 7, wherein the resonantly photo-pumping step comprises the step of generating a quantity of fluorine-like vanadium ions, in the $\overline{2p}_{3/2}\overline{2p}_{\frac{1}{2}}3d_{3/2}$ (J=5/2) and $\overline{2p}_{\frac{1}{2}}\overline{2p}_{\frac{1}{2}}3d_{3/2}$ (J=3/2) states, in spatial and temporal proximity to the quantity of neon-like titanium ions, whereby the resonant photo-pumping occurs on $\overline{2p}_{3/2}\overline{2p}_{\frac{1}{2}}3d_{3/2}$ (J=5/2)$\rightarrow\overline{2p}_{3/2}$ and $\overline{2p}_{\frac{1}{2}}\overline{2p}_{\frac{1}{2}}3d_{3/2}$ (J=3/2)$\rightarrow\overline{2p}_{\frac{1}{2}}$ (J=$\frac{1}{2}$) emission lines in the fluorine-like vanadium.

9. A method for providing x-ray laser radiation comprising the step of resonantly photo-pumping titanium ions to upper states by simultaneously illuminating the opposite sides of a combination comprised of a vanadium foil that has a titanium film deposited on one side thereof, with a first and a second beam of line focused, high power optical laser radiation, over adjacent, long and thin and generally rectangular portions of the vanadium an titanium combination.

10. The method of claim 9 wherein the step of resonantly photo-pumping includes applying a prepulse of energy to the titanium film to produce titanium plasma in the ground state.

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United States Patent [19]

Tomie

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[45] Date of Patent: Mar. 8, 1994

[54] **PLASMA GENERATING APPARATUS AND METHOD FOR EXTREME-ULTAVIOLET LASER**

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[51] Int. Cl.[5] H01S 3/30

[52] U.S. Cl. 372/5; 372/55

[58] Field of Search 372/5, 55, 89, 90, 91, 372/103, 701; 315/111.21, 111.81

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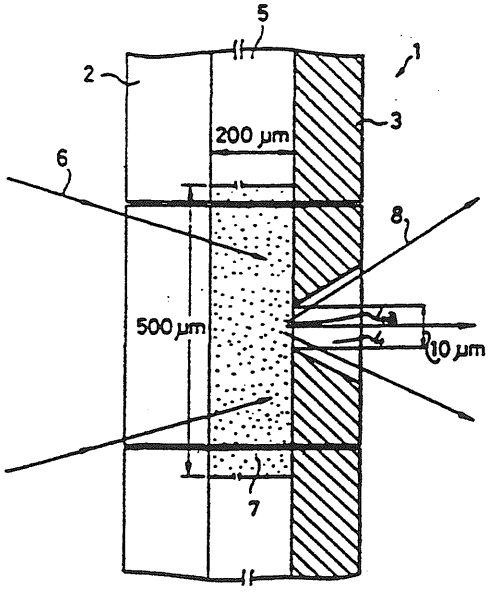
[57] ABSTRACT

A plasma generating apparatus for an extreme-ultraviolet laser that can generate high temperature plasma at high efficiency, and can form long plasma to be recombined by rapid cooling of the high temperature plasma. A shield plate including a narrow slit is disposed adjacent to a high temperature plasma source, and the high temperature plasma is discharged through the slit. Both high efficiency plasma generation and rapid expansion thereof can be simultaneously achieved by discharging high temperature plasma through the narrow slit. The rapid expansion makes it possible to form a long plasma having a large gain in an extreme-ultraviolet region. The high temperature plasma source can be readily realized by irradiating it with an exciting laser beam from behind the opposite side of the slit with regard to the high temperature plasma source directly or through a transmitting window. A closure provided in front of the slit can prevent a liquid or gas from flowing out of the slit before it is changed into plasma. This makes it possible to use a liquid or gas as a plasma source material.

18 Claims, 2 Drawing Sheets



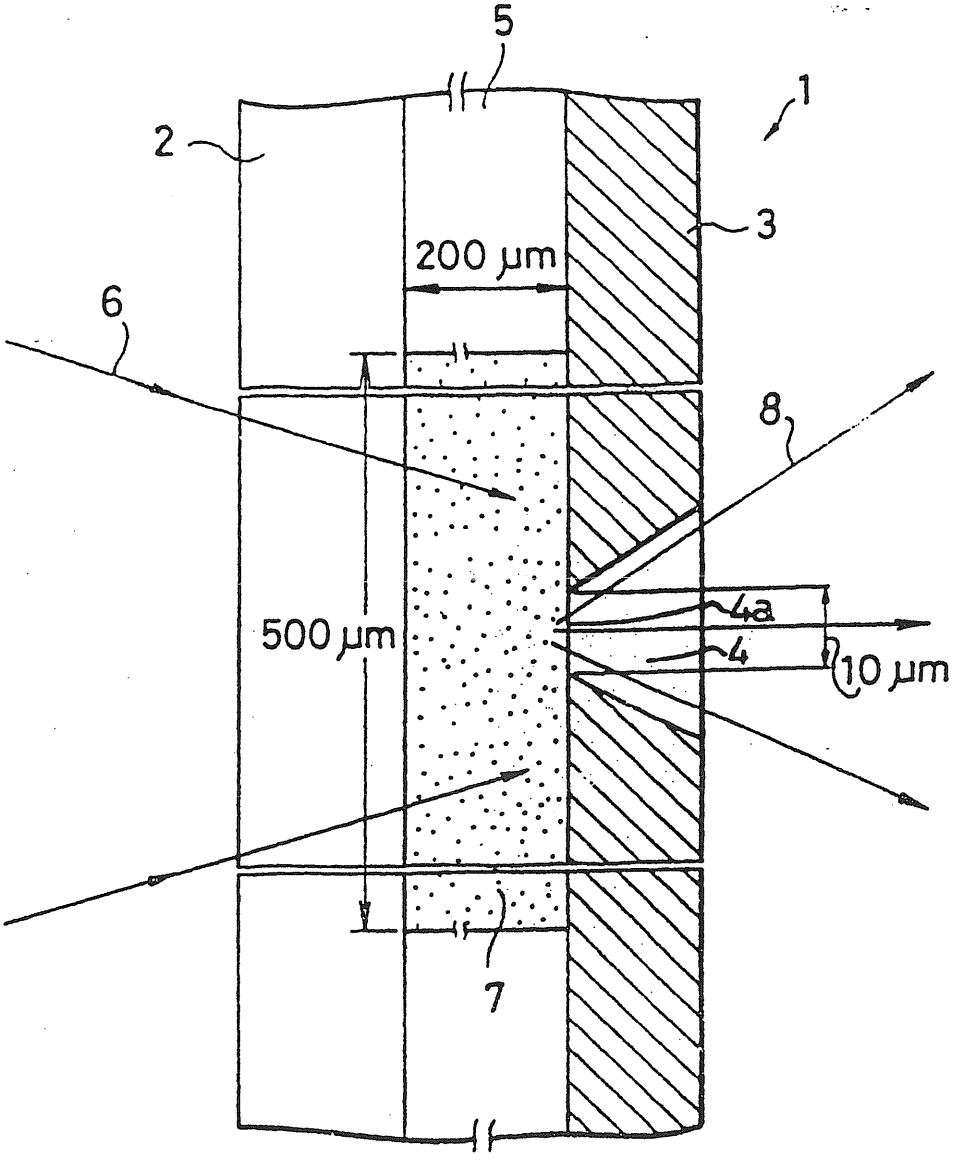


FIG. 1

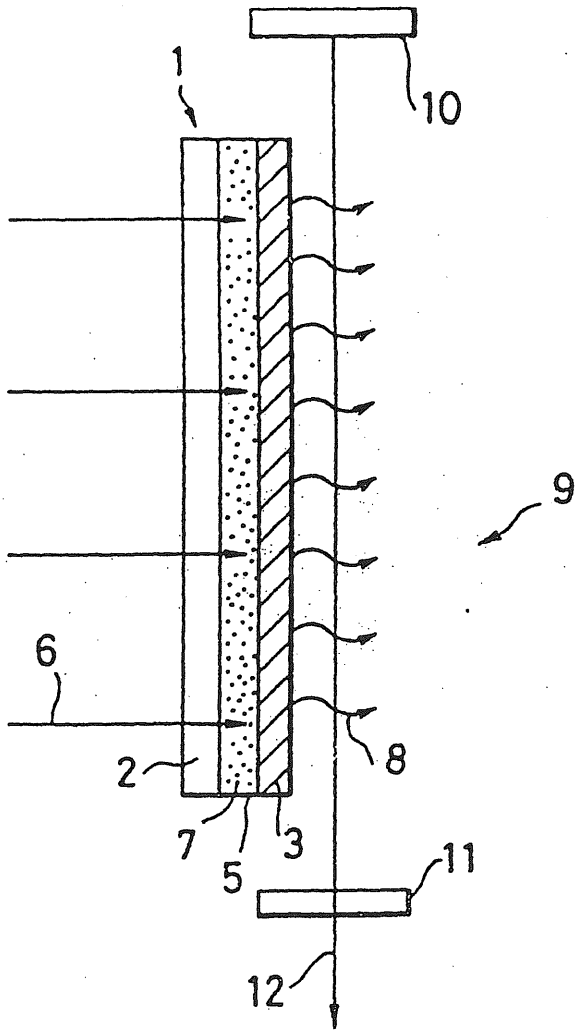


FIG. 2

PLASMA GENERATING APPARATUS AND METHOD FOR EXTREME-ULTAVIOLET LASER

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a plasma generating apparatus and method for an extreme-ultraviolet laser.

2. Description of the Related Art

Since the invention of a laser, efforts to shorten wavelengths of lasers have been continued, and as the wavelengths of lasers have been shortened, fields of laser application have been gradually widened. Recently, in particular, extreme-ultraviolet lasers (which are often called an "X-ray laser") whose wavelength is less than 100 nm, have been extensively studied. To shorten the wavelengths of lasers, a great exciting power no less than fourth power of the reciprocal of a laser wavelength is required. This presents many physical and technical problems that must be solved before an extreme-ultraviolet laser is realized. One promising extreme-ultraviolet laser is a recombination laser. This laser attempts to achieve an extreme-ultraviolet amplification by rapidly cooling a high temperature plasma. The most rapid cooling method is an adiabatic expansion cooling, if the size of the initial hot plasma is small enough. This method is based on the principle that the temperature drop takes place when gases are subjected to free expansion because thermal motion of particles are changed into translational motion, accompanying the density reduction by the expansion. To achieve sufficient amplification of an extreme-ultraviolet laser, the degree of population inversion achieved in nonequilibrium state must be great. This requires that the temperature of a plasma must be dropped faster than the speed of progress toward the thermal equilibrium. That is, a rapid expansion is required.

A greater density reduction is accomplished when a cylindrical plasma expands radially than when a plane plasma expands linearly. Accordingly, greater amplification power of an extreme-ultraviolet laser will be expected with a cylindrical plasma. The difference anticipated with the plane plasma and the cylindrical plasma has been experimentally confirmed (T. Tomie et al., X-ray lasers 1990, ed. by G. Tallents, Institute of Physics Conference Series 116, 1990). The cylindrical plasma from which a rapid expansion is expected can be generated by irradiating a thin fiber by an exciting laser. It was experimentally confirmed that 18 nanometer extreme-ultraviolet light was amplified using a seven micrometer diameter carbon fiber as a target (C. Chenais-Popovics, et al., Physical Review Letters, volume 59, number 19 (1987)).

Although C. Chenais-Popovics et al., reported a moderate degree of amplification of extreme ultraviolet light of 18 nanometer wavelength using a seven micrometer diameter by eight millimeter long carbon fiber as a target, several centimeter long plasma is required to achieve a sufficient amplification and to realize a practical extreme-ultraviolet laser of sufficient energy. Since light travels in straight lines, the plasma must also maintain the straightness in order to amplify extreme-ultraviolet light rays. However, it is inevitable for a thin, seven micrometer diameter fiber to bend, and hence, it is almost impossible to generate more than two centimeter long straight plasma by a fiber target. Furthermore, it is impossible for a thin fiber to absorb exciting laser energy with high efficiency: in experiments, absorption fractions less than only 10% have been achieved.

SUMMARY OF THE INVENTION

It is therefore an object of the present invention to provide a plasma generating apparatus and method for an extreme-ultraviolet laser that can generate a rapidly expanding straight plasma of sufficient length at high heating efficiency, thereby eliminating the above described problems.

According to a first aspect of the present invention, there is provided a plasma generating apparatus for an extreme-ultraviolet laser comprising a high temperature plasma source which generates a high temperature plasma, a shield plate including a slit through which the high temperature plasma source is discharged, and exciting means for heating the high temperature plasma source from the opposite side of the slit.

Here, the exciting means may be an exciting laser beam, and the plasma generating apparatus may further comprise a window transmitting the exciting laser beam, the window and the shield plate forming a space between the window and the shield plate, the space confining a high temperature plasma generated by heating the high temperature plasma source with the exciting laser beam.

The exciting laser beam may irradiate the back of the high temperature plasma source from behind the window, and the slit is disposed in front of the high temperature plasma source.

The high temperature plasma source may be generated from a solid material.

The high temperature plasma source may be generated from a liquid material or a gaseous material.

The shield plate may further comprise closure means for closing the slit until discharge of the high temperature plasma.

According to a second aspect of the present invention, there is provided a plasma generating method for an extreme-ultraviolet laser comprising the steps of heating a material to generate a high temperature plasma source, the heating being carried out from behind the high temperature plasma source, and discharging, through a slit in front of the high temperature plasma source, the high temperature plasma of the high temperature plasma source.

According to a third aspect of the present invention, there is provided a recombination laser comprising at least one resonant laser cavity including a mirror and an output mirror, a high temperature plasma source which generates a high temperature plasma, a shield plate including a slit through which the high temperature plasma of the high temperature plasma source is discharged into the resonant laser cavity, and exciting means for heating the high temperature plasma source from the opposite side of the slit.

The plasma generating apparatus for an extreme-ultraviolet laser of the present invention comprises the high temperature plasma source and the shield plate including a narrow slit through which the high temperature plasma in the high temperature plasma source expands rapidly. Thus, it can generate a rapidly expanding straight plasma of a sufficient length.

In addition, the present invention may further comprise the window transmitting the exciting laser beam, which window confines the high temperature plasma

within the space between the window and the shield plate.

Moreover, the closure may be provided on the shield plate to close the slit to employ a liquid or gas as a material for the plasma source.

The above and other objects, effects, features and advantages of the present invention will become more apparent from the following description of the embodiments thereof taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a sectional side view showing a major portion of an embodiment of a plasma generating apparatus for an extreme-ultraviolet laser according to the present invention; and

FIG. 2 is a schematic plan view showing a major portion of an extreme-ultraviolet laser incorporating the plasma generating apparatus of FIG. 1.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

The invention will now be described with reference to the accompanying drawings.

FIG. 1 is a sectional side view showing an embodiment of a plasma generating apparatus for an extreme-ultraviolet laser according to the present invention.

In this figure, reference numeral 1 designates a part of a plasma generating apparatus. The complete apparatus 1 comprises a plurality of such parts repeated in cascade as shown in FIG. 2. The plasma generating apparatus comprises a high temperature plasma source 7 and a shield plate 3. The plasma generating apparatus can further comprise a transmitting window 2 to confine the plasma source 7 within a space created by the shield plate 3, a spacer 5, and the window 2.

The shield plate 3 has a slit 4 which is about ten micrometers wide or less by several centimeters long in the direction normal to the sheet of FIG. 1. High temperature plasma in the high temperature plasma source 7 is discharged through the slit 4. The plasma source is generated by irradiating a material for the plasma source with an exciting laser beam 6. The wall of the space for the plasma source 7, thin film placed in the space, or a liquid or gas confined in the space can be a material for the plasma source. The material of the window 2 can be solid or plasma. It is not essential to use the transmitting window 2 when a material for the plasma source is solid. In this case, the window 2 can enhance the expansion velocity of the plasma through the slit 4.

When the solid transmitting window 2 is irradiated by the intense laser beam 6, the material making up the window 2 might be ionized into a plasma, which prevents the exciting laser beam 6 from reaching the material for the plasma source 7. To avoid this, the laser beam 6 is sharply focused onto the material of the plasma source 7 so that the density of the exciting laser beam 6 is reduced at the transmitting window 2. Alternatively, the transmitting window 2 can be a plasma initially made of a very thin film less than one micrometer thick. After the very thin film is ionized into a plasma by absorbing the laser beam 6, it can transmit the laser beam 6 when the density of the plasma is reduced by the expansion. The thin film plasma can have power to increase the discharging speed of the high temperature plasma from the slit 4. Furthermore, when a liquid or gaseous material is used as the material for plasma source 7, the thin film can prevent the effluent of the plasma source material out of the space prior to the irradiation of the exciting laser.

The space confining the high temperature plasma source 7 is several hundred micrometers both in width and thickness, although its sizes must be changed depending on the type of exciting lasers or other conditions. Although the high temperature plasma source 7 is usually generated by irradiating a solid material such as a carbon fiber or aluminum thin film with the exciting laser beam, any of the liquid, gaseous and solid materials can be employed as a material of the plasma source 7. For example, oxygen, carbon, nitrogen, etc., can be used. The walls of the space for the high temperature plasma source 7 might be ionized into a high temperature plasma source. Hence, the surface material of the walls must be such as not changing the composition of the high temperature plasma source 7.

The shield plate 3 is preferably made of silicon, through which the slit 4 is easily formed by etching process. Any other material may be employed of which 10 micrometer wide or less by several centimeter long slit 4 can be formed. When a liquid or gaseous material is used as the high temperature plasma source 7, the slit 4 is closed in advance by a closure 4a made of a very thin film about 0.1 micrometer thick or less. Thus, the effluent of the liquid or gas from the space is prevented.

Various lasers can be employed as an exciting laser that emits the exciting laser beam 6, and is chosen considering the type of the extreme-ultraviolet laser to be implemented. To provide a rather long wavelength extreme-ultraviolet laser, a far-infrared carbon dioxide gas laser or an infrared glass laser is suitable for the exciting laser. In this case, the pulse width may range from several nanoseconds to several tens of nanoseconds. On the other hand, to produce a short wavelength extreme-ultraviolet laser, a short wavelength exciting laser such as an excimer laser that produces ultraviolet light is suitably used. In this case, a very short pulse of the order of picoseconds in width is thought to be appropriate, although a pulse a few nanoseconds wide or longer may also be used. The power of the laser also changes depending on the type of lasers and the kind of high temperature plasma source 7. When the high temperature plasma is composed of fully ionized carbon ions which are produced by exciting with glass laser pulses several nanoseconds wide, irradiation power of 10^{12} W/cm^2 is required. On the other hand, when the high temperature plasma is composed of fully ionized aluminum ions which are produced by exciting with excimer laser pulses several picoseconds wide, irradiation power of at least 10^{15} W/cm^2 is required.

Next, the operation of the apparatus will be described. The high temperature plasma in the high temperature plasma source 7 is discharged through the slit 4 of the shield plate 3, resulting in a rapid temperature drop of the plasma by expansion. This abrupt temperature drop provides the discharged plasma 8 in a transitional nonequilibrium state with power to amplify extreme-ultraviolet light rays. Thus, a laser amplification of extreme-ultraviolet light rays is achieved. A resonator 9 as shown in FIG. 2 can be incorporated to enhance the amplification.

The high temperature plasma source 7 can be generated by heating the material for the source with the exciting laser beam 6. When the high temperature plasma source is generated by irradiating a solid mate-

rial, the high temperature plasma reaching the slit 4 is pressed by the pressure of plasma at the back, and is discharged through the slit 4, resulting in a rapid expansion. On the other hand, when the high temperature plasma is generated by irradiating a liquid or gaseous material, the slit 4 is closed in advance by the closure 4a made of a very thin film about 0.1 micrometer thick or less. This can prevent the liquid or gas from flowing out of the space confining the high temperature plasma source 7. Once the high temperature plasma source 7 is generated with the irradiation of the exciting laser beam 6, the closure 4a is broken by the pressure thereof, and the plasma discharges through the slit 4. The optimum temperature of the high temperature plasma source 7 is greatly different depending on the wavelength of the extreme-ultraviolet laser to be implemented: when its wavelength is about 20 nm, plasma temperature of about 100 eV (one million degrees) is required; and when its wavelength is about 4 nm, plasma temperature of about 1000 eV (ten million degrees) is required.

By using the transparent window 2 that transmits the exciting laser beam 6, the high temperature plasma source 7 can be confined within the space. This confinement of the high temperature plasma source 7 with the window 2 makes it possible to increase the discharge speed through the slit 4. To achieve a rapid density drop of the discharged plasma 8, the slit 4 must be extremely narrow.

Thus, the rapid expansion, which enables rapid cooling of the high temperature plasma source 7, can be realized by discharging the high temperature plasma source 7 through the narrow slit 4 formed in the shield plate 3. The use of the shield plate 3 which is far more robust than a fiber makes it possible to form the straight discharged plasma 8 of sufficient length. To generate the high temperature plasma source 7 behind the shield plate 3, the energy injection through the slit 4 must be avoided. This is because, although the high temperature plasma source 7 could be generated behind the shield plate 3 by injecting energy through the narrow slit 4, it is unavoidable for the energy to be absorbed by the shield plate 3, which will generate a new plasma surrounding the discharged plasma that prevents the plasma 8 discharged through the slit 4 from expanding rapidly.

The space for the high temperature plasma source behind the shield plate 3 need not to be so narrow: for example, one millimeter wide high temperature plasma source 7 can be discharged through the 10 micrometer wide slit 4. Therefore, the high temperature plasma source 7 is easily generated, and various steps can be taken to increase the energy injection efficiency of the plasma. For example, in the case where the exciting laser beam 6 cannot be focused smaller than a 100 micrometer diameter, a 10 micrometer diameter fiber employed as a target can use, in brief, only 10% of energy, wasting 90% of energy that does not irradiate the target. On the other hand, the total exciting energy can be used to generate the plasma by the present invention. When a fiber is used as a target, materials of the fiber are limited: only such materials that can be drawn into a thin straight fiber, or that can be deposited onto the straight thin fiber. The present invention, however, can employ not only various kinds of solid, but also liquids or gases, as a material for the plasma source. When a liquid or gas is employed as a material for the plasma source, the slit 4 must be closed so as to prevent the material from flowing out of the slit 4 before it is converted into a plasma by the injection of energy. This can be realized by closing the slit 4 in advance with a means like a thin film as stated before, or with a shutter that can open and close the slit 4 mechanically.

By irradiating the target in the space between the window 2 and the shield plate 3 with the exciting laser beam 6 through the window 2 which is made of a material transparent to the laser beam 6, the high temperature plasma source 7 to be discharged through the slit 4 can be effectively generated behind the shield plate 3. In this case, the material for the plasma source may be a solid material placed between the window 2 and the shield plate 3, or a gas or liquid target retained within the space. The irradiation of the exciting laser beam 6 onto the space retaining the plasma source can also be achieved by using the multiple reflections of mirrors, or by using optical fibers. In addition, confinement of the plasma by employing magnetic field is possible. As the energy source for generating the high temperature plasma source 7, heating with particle beam, Z pinch, the radio frequency or the like is possible.

The mass of the high temperature plasma source 7 will be declined by the discharge, when the irradiation with the exciting laser beam 6 is stopped. As a result, the pressure of the high temperature plasma source 7 also declines, resulting in the decrease in the discharging speed. In contrast, when the irradiation with the exciting laser beam 6 is continued, the mass of the high temperature plasma source 7 can be maintained at a fixed value. This will make it possible to implement an extreme-ultraviolet laser that oscillates continuously. In this case, however, the increase in a discharged plasma mass in front of the slit 4 might hinder the rapid expansion of the high temperature plasma through the slit 4, or hinder the operation of the extreme-ultraviolet laser. In order to alleviate this problem, intermittent irradiation of the exciting laser beam 6 will be effective.

In existing extreme-ultraviolet lasers employing a thin film, a slab or a fiber as a target, the duration of oscillation is on the order of subnanoseconds, or several tens of nanoseconds at most. The extreme-ultraviolet laser according to the present invention can provide a longer oscillating duration.

FIG. 2 is a schematic plan view showing a major portion of an extreme-ultraviolet laser incorporating the plasma generating apparatus of FIG. 1. In FIG. 2, like reference numerals designate like portions in FIG. 1. The extreme-ultraviolet laser further comprises a resonator 9, which is constructed by an extreme-ultraviolet light reflection mirror 10, and an extreme-ultraviolet light half mirror (an output mirror) 11. With this arrangement, an output 12 of the extreme-ultraviolet laser is produced from the output mirror 11.

Although a specific embodiment of a plasma generating apparatus and method for an extreme-ultraviolet laser constructed in accordance with the present invention has been disclosed, it is not intended that the invention be restricted to either the specific configurations or the uses disclosed herein. Modifications may be made in a manner obvious to those skilled in the art. Accordingly, it is intended that the invention be limited only by the scope of the appended claims.

What is claimed is:

1. A plasma generating apparatus for an extreme-ultraviolet laser comprising:

a high temperature plasma source which generates a high temperature plasma;

a shield plate including a slit through which said high temperature plasma of said high temperature plasma source is discharged; and

exciting means for heating said high temperature plasma source from the opposite side of said slit.

2. The plasma generating apparatus for an extreme-ultraviolet laser as claimed in claim 1, wherein said exciting means is an exciting laser beam, and further comprising a window transmitting said exciting laser beam, said window and said shield plate forming a space between said window and said shield plate, said space confining a high temperature plasma generated by heating said high temperature plasma source with said exciting laser beam.

3. The plasma generating apparatus for an extreme-ultraviolet laser as claimed in claim 2, wherein said exciting laser beam irradiates the back of said high temperature plasma source from behind said window, and said slit is disposed in front of said high temperature plasma source.

4. The plasma generating apparatus for an extreme-ultraviolet laser as claimed in claim 1, wherein said high temperature plasma source is generated from a solid material.

5. The plasma generating apparatus for an extreme-ultraviolet laser as claimed in claim 1, wherein said high temperature plasma source is generated from a liquid material or a gaseous material.

6. The plasma generating apparatus for an extreme-ultraviolet laser as claimed in claim 5, wherein said shield plate further comprises closure means for closing said slit until discharge of said high temperature plasma.

7. A plasma generating method for an extreme-ultraviolet laser comprising the steps of:

heating a material to generate a high temperature plasma source, said heating being carried out from behind said high temperature plasma source; and

discharging, through a slit in front of said high temperature plasma source, said high temperature plasma of said high temperature plasma source.

8. The plasma generating method for an extreme-ultraviolet laser as claimed in claim 7, wherein said heating is carried out by irradiation of an exciting laser beam transmitted through a window disposed behind said high temperature plasma source.

9. The plasma generating method for an extreme-ultraviolet laser as claimed in claim 8, wherein said exciting laser beam is irradiated to the back of said high temperature plasma source from behind said window.

10. The plasma generating method for an extreme-ultraviolet laser as claimed in claim 7, wherein said high temperature plasma source is generated from a solid material.

11. The plasma generating method for an extreme-ultraviolet laser as claimed in claim 7, wherein said high temperature plasma source is generated from a liquid material or a gaseous material.

12. The plasma generating method for an extreme-ultraviolet laser as claimed in claim 11, further comprising the step of closing said slit by a closure until discharge of said high temperature plasma.

13. A recombination laser comprising:

at least one resonant laser cavity including a mirror and an output mirror;

a high temperature plasma source which generates a high temperature plasma;

a shield plate including a slit through which said high temperature plasma of said high temperature plasma source is discharged into said resonant laser cavity; and

exciting means for heating said high temperature plasma source from the opposite side of said slit.

14. The recombination laser as claimed in claim 13, wherein said exciting means is an exciting laser beam, and further comprising a window transmitting said exciting laser beam, said window and said shield plate forming a space between said window and said shield plate, said space confining said high temperature plasma generated by heating said high temperature plasma source with said exciting laser beam.

15. The recombination laser as claimed in claim 14, wherein said exciting laser beam irradiates the back of said high temperature plasma source from behind said window, and said slit is disposed in front of said high temperature plasma source.

16. The recombination laser as claimed in claim 13, wherein said high temperature plasma source is generated from a solid material.

17. The recombination laser as claimed in claim 13, wherein said high temperature plasma source is made generated from liquid material or a gaseous material.

18. The recombination laser as claimed in claim 17, wherein said shield plate further comprises closure means for closing said slit until discharge of said high temperature plasma.

* * * * *

US005317574A

United States Patent [19]

Wang

[11] Patent Number: 5,317,574

[45] Date of Patent: May 31, 1994

[54] METHOD AND APPARATUS FOR GENERATING X-RAY AND/OR EXTREME ULTRAVIOLET LASER

[76] Inventor: [illegible], #108, San Ramon, Calif. 94583

[21] Appl. No.: 999,127

[22] Filed: Dec 31, 1992

[51] Int. Cl.[5] H01S 3/097; H01S 3/30

[52] U.S. Cl. 372/5; 372/87

[58] Field of Search 372/5, 87

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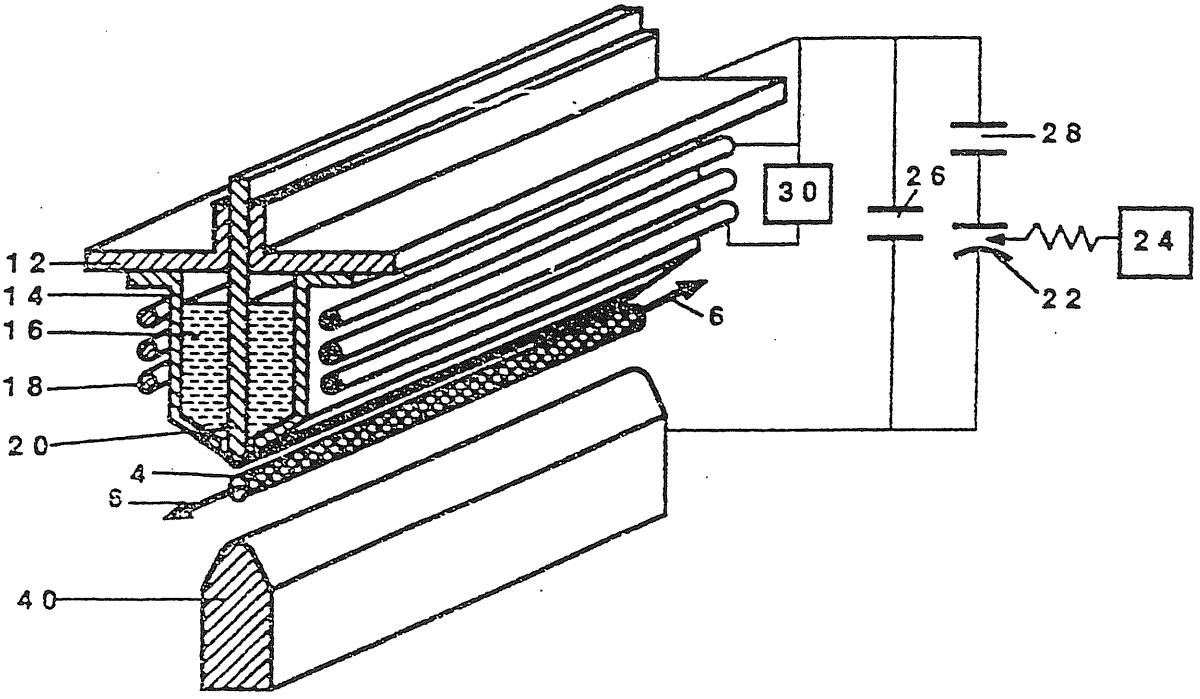
Primary Examiner—Frank Gonzalez

[57] ABSTRACT

A method and apparatus for producing x-ray and/or extreme ultraviolet (EUV) is described. A liquid edge 2 is electrically connected to a cathode 8 via a high voltage pulse power supply 10. Liquid edge 2 is set to be parallel to cathode 8. When high voltage pulse power supply 10 is turned on, a vacuum discharge will occur in a space between liquid edge 2 and cathode 8. The plasma will be confined into a high density and high temperature thin plasma column 4 in a space near liquid edge 2 by strong magnetic field induced by the huge discharge current. A population inversion in the confined plasma column will lead to a amplified simultaneous emission of x-ray and/or EUV 6 along the axis of plasma column 4. Moreover, a large power x-ray and/or EUV laser can be built by using multi-liquid edge-shape anodes placed in a straight line and operated in a traveling-wave mode.

31 Claims, 8 Drawing Sheets



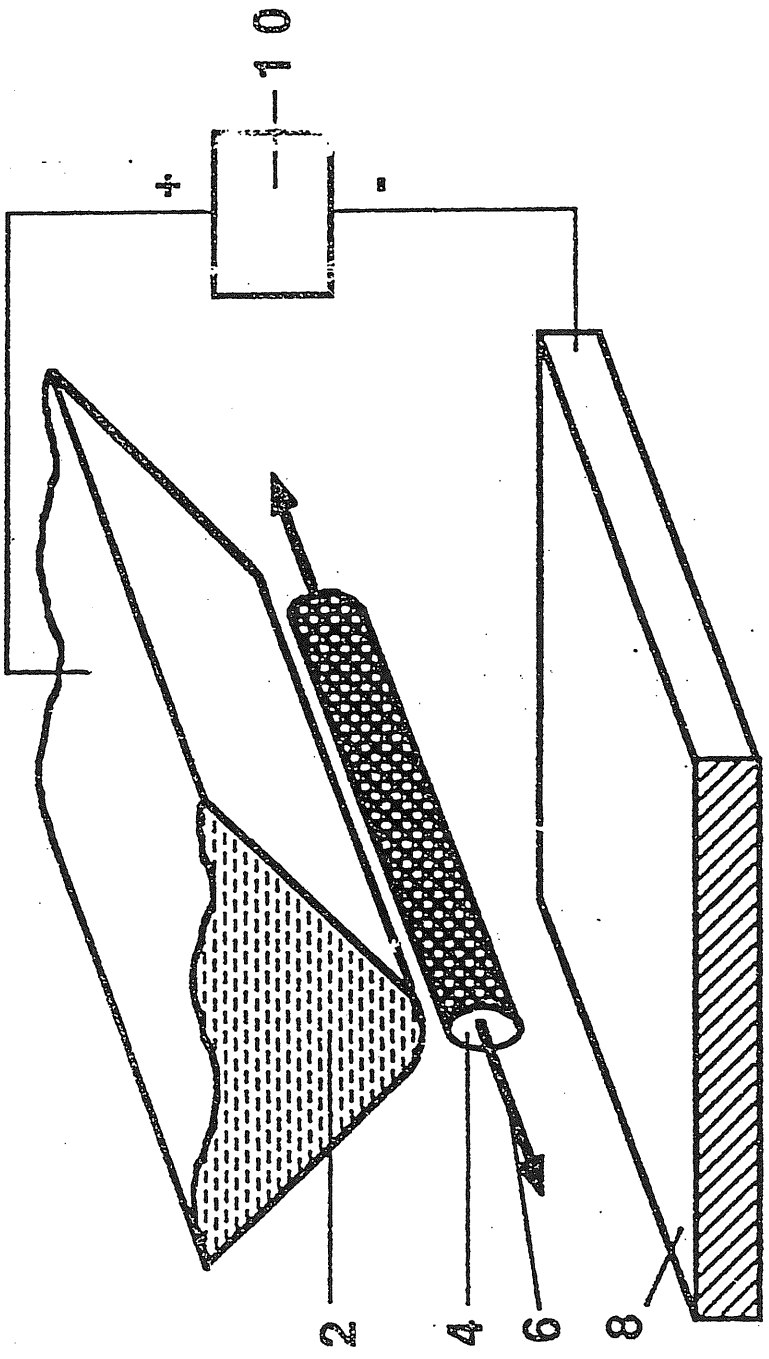


FIG.1

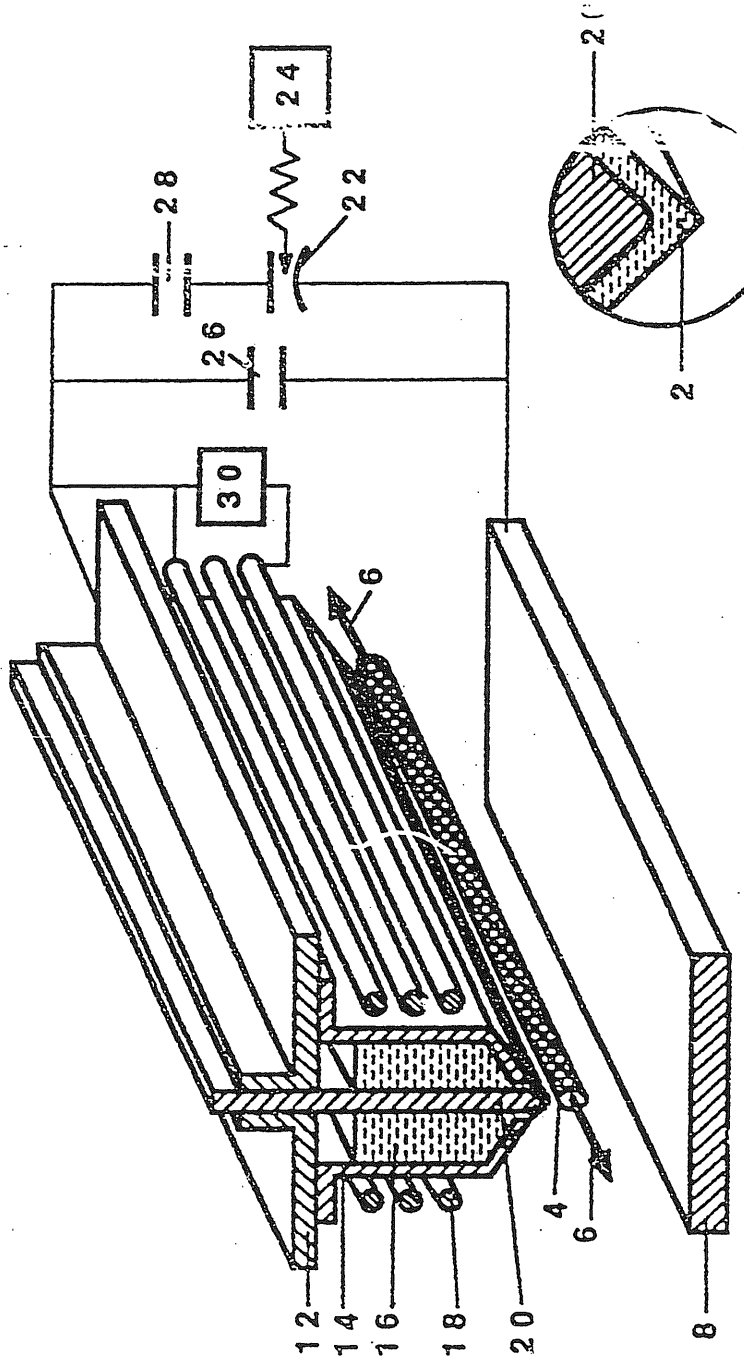


Fig.2A

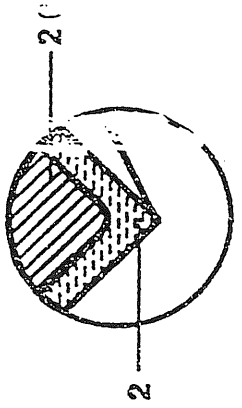


Fig.2B

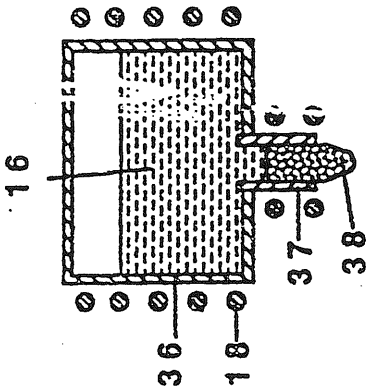


FIG.3 C

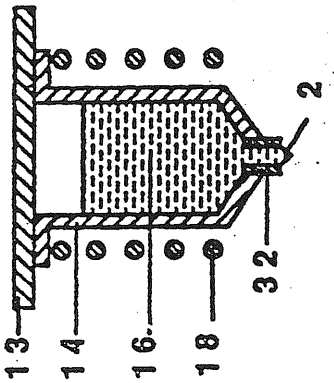


FIG.3 B

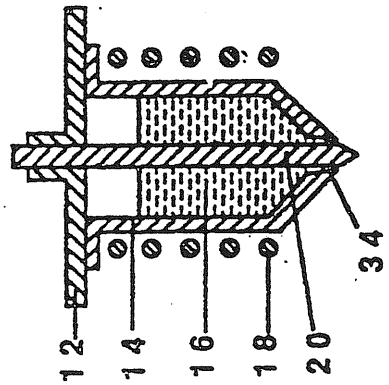


FIG.3 A

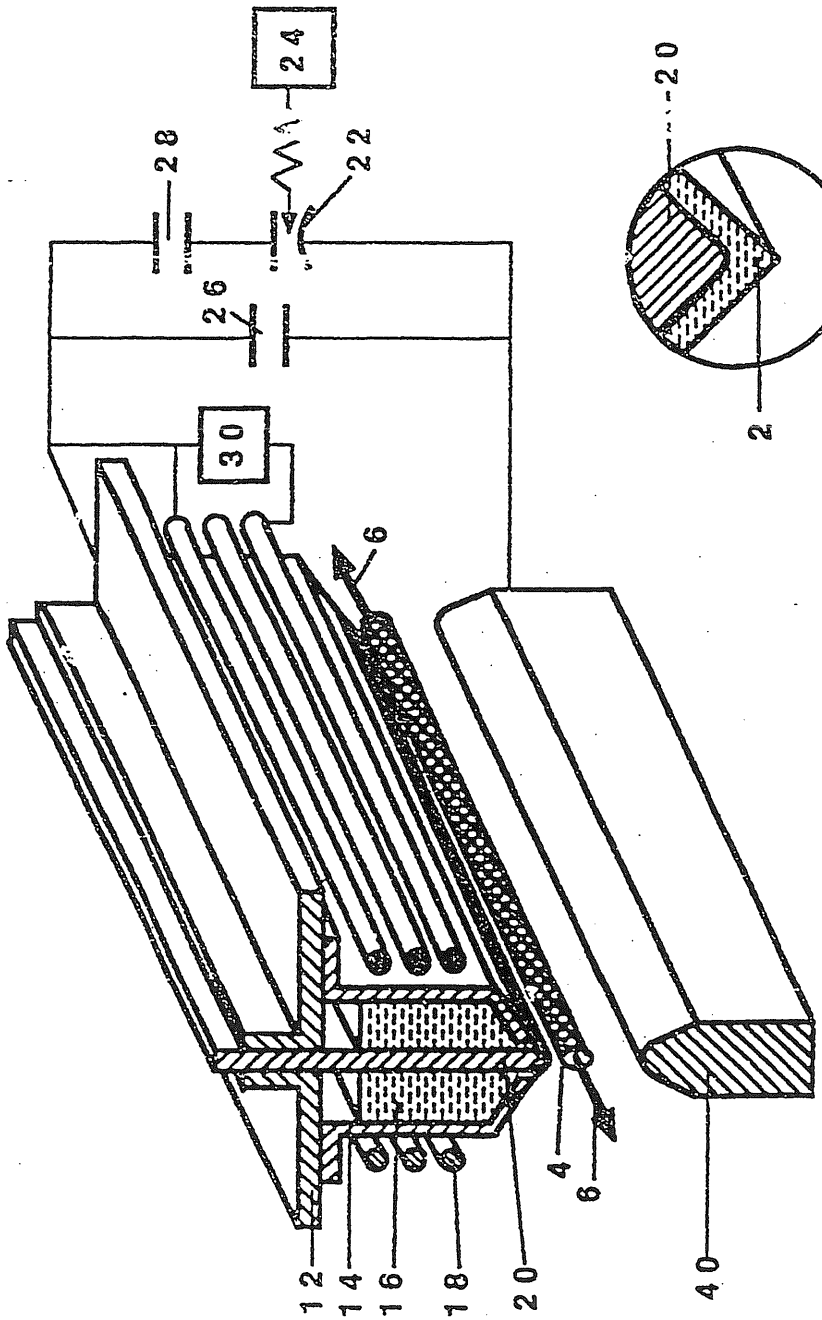


Fig.4A

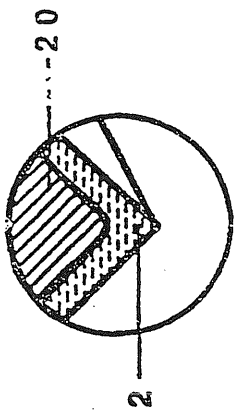


Fig.4B

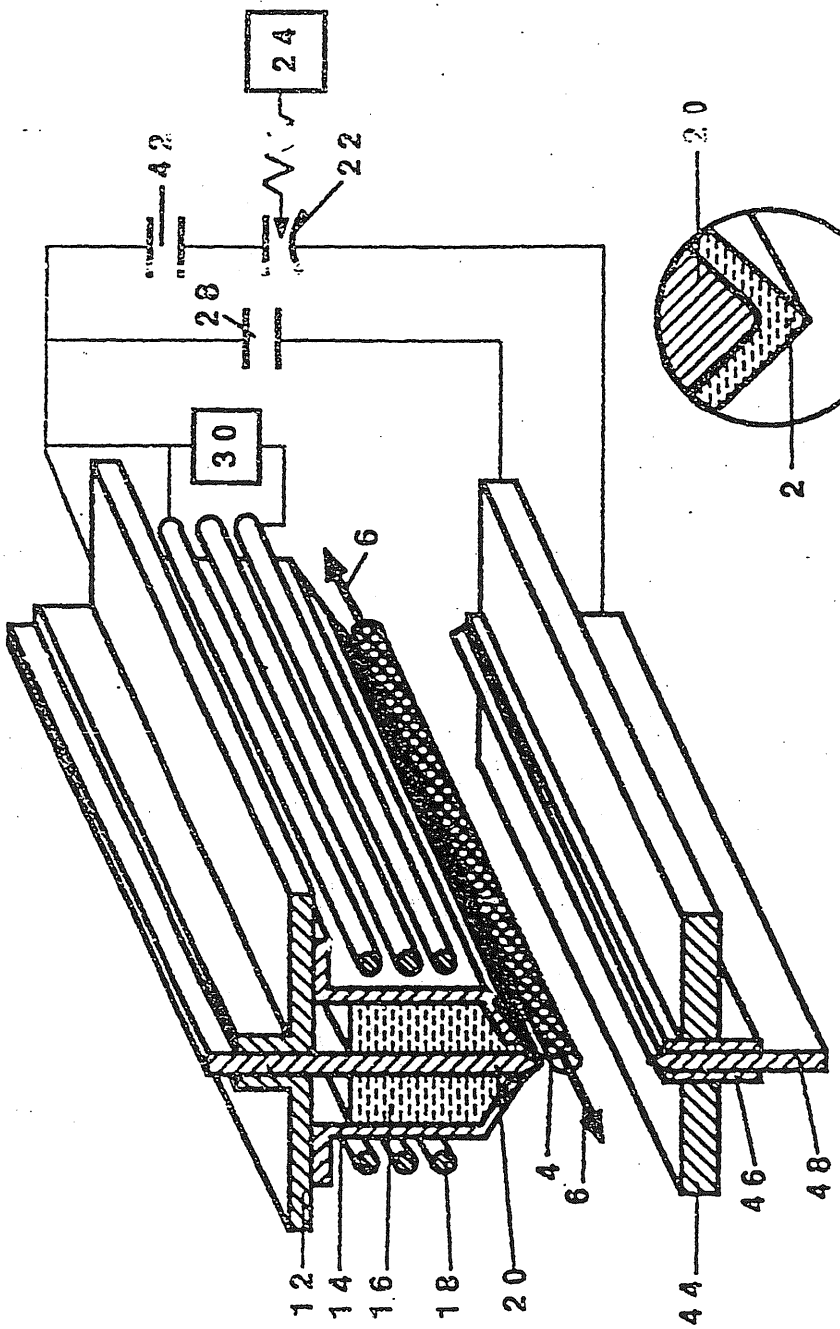


Fig.5A

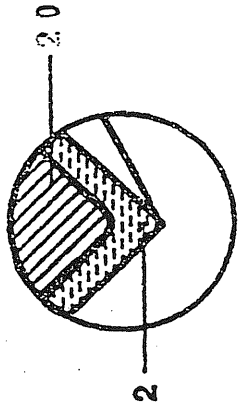


Fig.5B

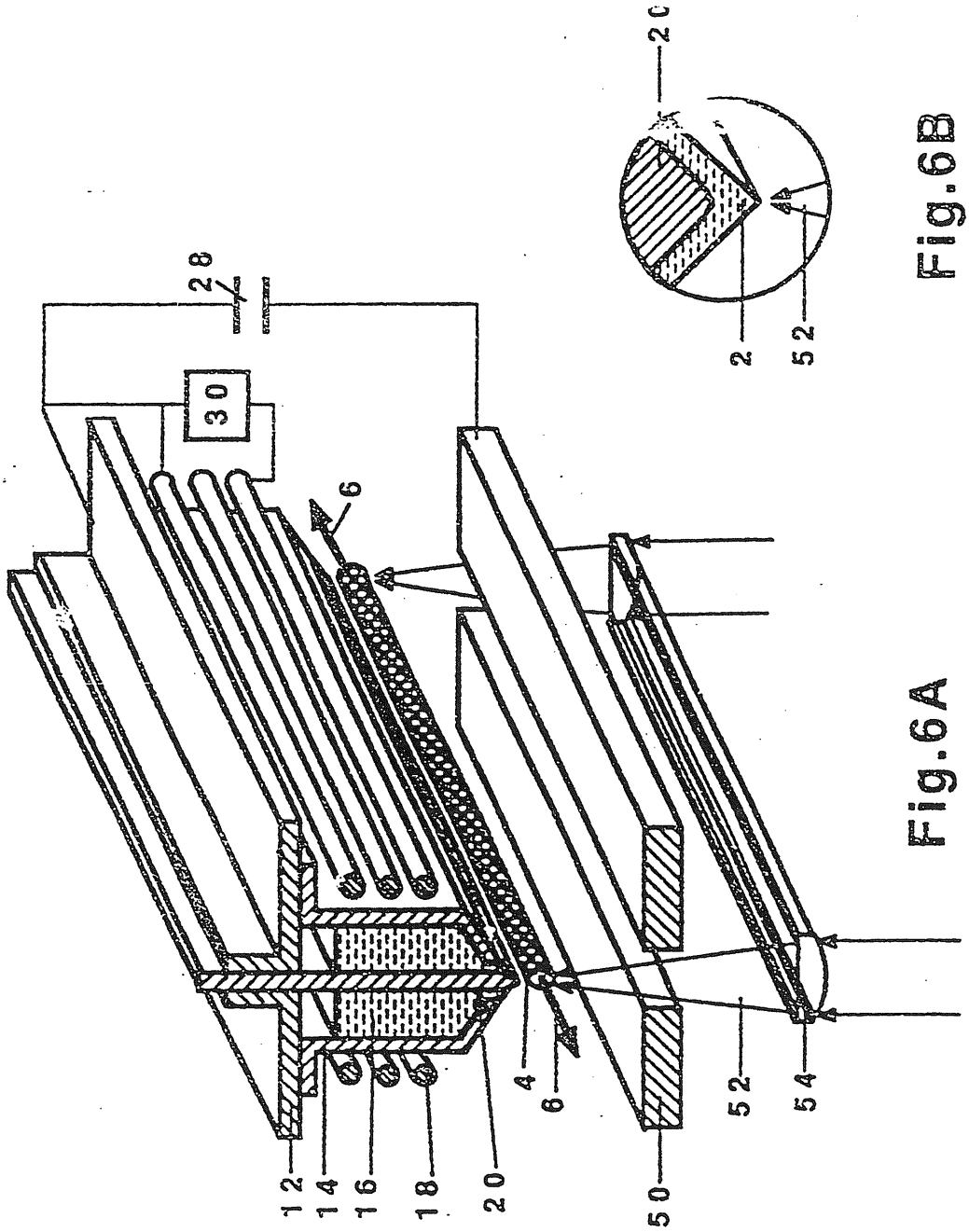


Fig.6A

Fig.6B

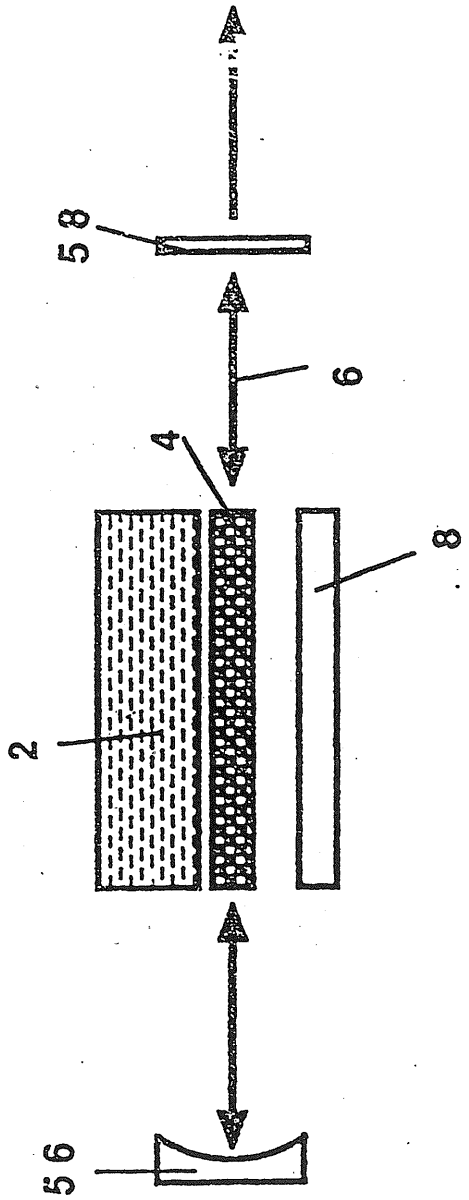


Fig.7

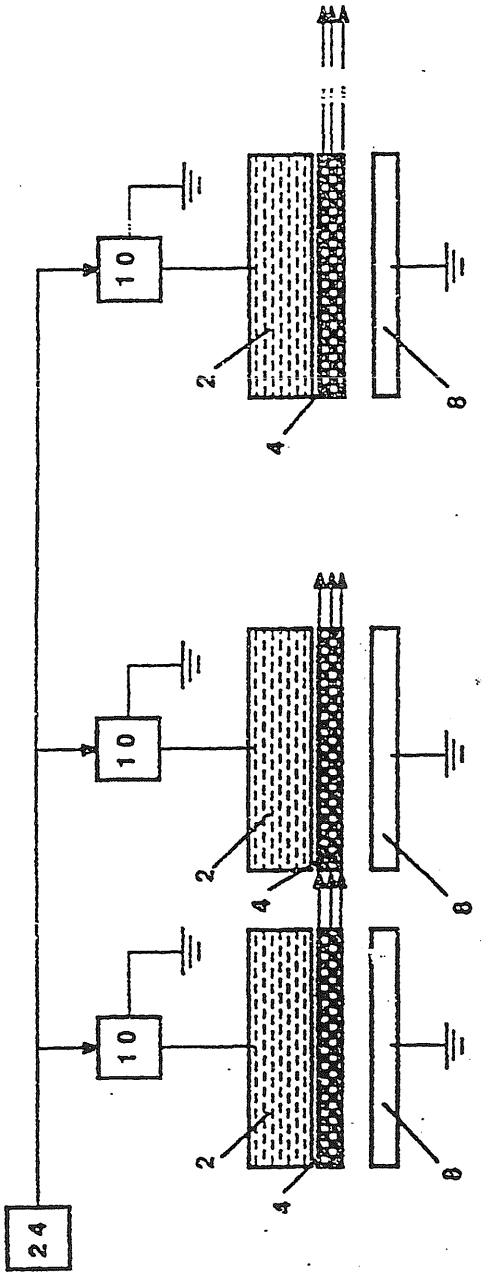


Fig.8

METHOD AND APPARATUS FOR GENERATING X-RAY AND/OR EXTREME ULTRAVIOLET LASER

TECHNICAL FIELD

The instant invention relates to a novel method and apparatus for generating a large power, high efficiency, and low cost X-ray laser and/or extreme ultraviolet (EUV) laser.

BACKGROUND OF THE INVENTION

The basic requirement of any laser is existence of population inversion between two atomic or molecular states in a gaseous or a solid material so that energy by stimulated emission may yield amplification. The production of population inversion needs pumping energy. In the case of conventional laser, the photon energies are eV order, and transition lifetime is nanosecond order. However, in the case of X-ray lasers the photon energies are hundreds or thousands eV order, and the transition life time is less than picosecond. This means that X-ray laser needs a large amount of pumping energy to be brought into the active medium in a very short time.

Much efforts have been done toward the development of x-ray and/or extreme ultraviolet (EUV) laser since the conventional lasers appeared in 1960. It was not until recently that soft x-ray lasers were successfully operated. The first operational laboratory X-ray laser is reported by Rosen et al in Physical Review Letters 54, 106 (1985), and experimentally demonstrated by Matthews et al in Physical Review Letters 54, 110 (1985). This seminal X-ray laser system is also fully disclosed by Campbell et al in U.S. patent application Ser. No. 676,338 filed Nov. 29, 1984. A related short wavelength laser, whose output extends into the EUV and X-ray region, is disclosed by Hagelstein in U.S. Pat. No. 4,589,113 issued May 13, 1986. However, those soft x-ray lasers are very large apparatus requiring very large energy lasers as the excitation source, typically delivering laser pulses of hundreds of Joules to kilojoules at longer wavelength. The cost, complexity, and size of the equipment required to form such x-ray laser apparatus make them impractical for most technical and scientific applications. Another disadvantage of these types of lasers is the low energy converting efficiency. This is because the energy converting process is from the electrical energy into long wavelength laser radiation, and then using the long wavelength laser to create a plasma from which the x-ray laser light emits.

Another approach for generating a x-ray laser is to directly deposit electrical energy in a plasma column which lases x-ray. These types of x-ray lasers are more direct and potentially more efficient than those driven by conventional laser drivers. Moreover, they use capacitors as energy sources to excite the plasma, and the size of the capacitor storing the same amount of energy as that of the laser driver output is much smaller than the size of the laser driver. There are two types of electrical discharge x-ray lasers: 1) Z-pinch discharge; 2) Capillary discharge. A power of 25 GW has been measured from 11 Å spectral line in Z-pinch discharge by J. P. Apruzese, et al. in SPIE Proc. 875, 2 (1988). However, this Z-pinch x-ray laser is difficult to be combined with resonator for making large power, high coherent x-ray laser. In the capillary discharge type x-ray laser, a capillary tube is used to confine a column plasma which

lases x-ray. The pulse duration in most of such capillary discharge type x-ray lasers tested to date is in the 100's of nanoseconds range. Because of interactions with the wall of the capillary on such time scales, the temperature of plasma has been limited to a few tens of eV. Therefore, the capillary discharge is difficult to be used for generating x-ray laser in a wavelength shorter than 100 Å.

SUMMARY OF THE INVENTION

It is an object of the invention to provide a novel method and apparatus for producing X-ray and/or EUV laser.

It is an additional object of the invention to provide an electron collisional recombination pumped x-ray and/or EUV laser.

It is a further object of the invention to provide an electron-collisional recombination pumped x-ray and/or EUV laser.

It is a further object of the invention to provide a photoexcitation pumped x-ray and/or EUV laser.

It is still a further object of the invention to provide a charge transfer pumped x-ray and/or EUV laser.

It is a further object of the invention to provide an photoionization pumped x-ray and/or EUV laser.

It is still a further object of the invention to provide a large power multi-plasma-column X-ray laser.

The above and other objects of the invention are accomplished by the provision of a method for producing X-ray and/or EUV laser, comprising: forming an edge-shape anode electrode by liquid material; and generating a vacuum discharge between the anode electrode and the cathode electrode spaced apart from the anode electrode of sufficient huge discharge current to induce strong magnetic field to confine the plasma column in a space close to the anode. The confined plasma column lases x-ray and/or EUV laser.

In the further aspect of the invention there is provided a apparatus for generating x-ray and/or EUV laser, comprising: a liquid edge-shape anode including liquid material, a reservoir for holding the liquid material, the reservoir having an opening for passage of the liquid material, and liquid material feeding and liquid edge forming means operatively associated with the reservoir for feeding liquid material through the opening in the reservoir and for forming a liquid edge-shape anode from the liquid material; an cathode opposite the liquid edge-shape anode; and pulse power supply means connected to the liquid edge-shape anode and cathode for generating a vacuum discharge of sufficient huge discharge current to induce strong magnetic field to confine the plasma to a thin column in a space close to the anode. X-ray and/or EUV laser is lased from the thin plasma column.

One important advantage of this apparatus is that a column plasma with high electron temperature and high density of ions of the desired specie of charge Z can be produced. This feature promotes generation of population inversion which is created by electron-collisional excitation hereinafter described.

ELECTRON-COLLISIONAL EXCITATION LASERS IN LIQUID EDGE-SHAPE ANODE DISCHARGE

The generation of population inversions by electron-collisional excitation is the one of the most useful mechanisms to create population inversion in the liquid edge-

shape anode discharge. Electron-collisional excitation is inherently cw in that the initial and final laser states are ground level, and that only one ionic specie is involved. It also has the advantage that lower-state opacity is often relatively low, so that diameters measured in fractions of millimeter and length in centimeters are reasonable scales. Because it operates on $\Delta n=0$ transitions, it requires high temperature electron to excite high-Z atoms into high-Z charged ion and a large amount of ionization energy. The features of huge discharge current and high discharge voltage in the liquid edge-shape anode discharge disclosed in this patent make above requirements be easily satisfied. It is also possible that both high electron temperature and a large density of ions of the desired specie of charge Z exist simultaneously. Of cause, it is necessary to adjust the discharge conditions such as voltage, current, and pulse length so that the electron temperature values at which significant excitation occurs have to be achieved before the plasma is over-ionized and the ions of the lasing specie Z destroyed. Also, the electron density should be controlled to be moderate to avoid refraction loss in the laser beam as it passes through the plasma column.

Using electron-collisional excitation in the liquid edge-shape anode discharge disclosed in this patent, laser action can be achieved, for example, in Neon-like ions(i.e., ions with electronic structure of a neutral neon atom), such as neon-like Ge^{22+} at 23.2 nm. Nickel-like ions are also a useful type of ions for the generation of the soft x-ray laser radiation.

ELECTRON-ION RECOMBINATION LASERS IN LIQUID EDGE-SHAPE ANODE DISCHARGE

The generation of population inversion by electron-ion recombination is another major mechanism to create populatio.. inversions in a liquid edge-shape anode discharge. Electron-ion recombination, sometime referred to as "three-body" recombination, is an inverse process to the electron-collisional ionization from excited levels. This happens when plasma rapidly cools at the end of the excitation pulse by either adiabatic expansion, radiation or electron heat conduction. The rapid decrease in the plasma temperature causes the electrons and ions from the plasma to recombine, creating population inversion between excited levels of the lesser charge ions. Again radiation with a photon energy corresponding to the energy difference between the inverted levels is amplified. In this recombination process, the most important thing is rapid cooling. In the present invention, large electron heat conduction from the hot column plasma to the liquid edge-shape anode adds to other heat losses, such as radiative losses, to rapidly cool the column plasma, inducing large electron-ion recombination rates. The electron heat conduction cooling rate can be enhanced by the close proximity of the liquid edge-shape anode to the column plasma. The distance between the liquid edge-shape anode and the column plasma can be adjusted by the discharge condition such as, voltage, current, pulse length, apex radius of the anode, geometry of the cathode and the distance between the anode and the cathode. Radiative losses can be enhanced by adding a heavy atom(high Z atom) to the liquid edge-shape anode discharge. Such heavy atoms can be introduced by mix liquid material with heavy atom material or by selectively introducing a gas containing heavy atoms. In any case, rapid recombination of highly ionized ions of charge $Z+1$ into excited levels of ions of charge Z induces the generation of population inversions in the ions of charge Z and results in the amplification at x-ray and EUV wavelengths. For the occurrence of laser action a plasma density has to be achieved such that a large density of ions with charge $Z+1$ is created. Nevertheless the plasma density has to remain below a maximum value at which collisional electron de-excitation of the laser's upper lever, or trapping of lower laser resonant radiation will destroy the population inversions.

PHOTOEXCITATION AND/OR PHOTOIONIZATION LASERS IN LIQUID EDGE-SHAPE ANODE DISCHARGE

Photoexcitation and/or photoionization can also produce population inversions in liquid edge-shape anode discharge. The hot plasma region near the core of column plasma acts as a flash lamp to produce x-ray radiation that can excite or ionize lower ionized atoms, or atoms from a different species that exist in the cooler plasma region that close to liquid edge-shape anode, thus a population inversion in cooler plasma region is created.

CHARGE TRANSFER COLLISIONAL LASERS IN LIQUID EDGE-SHAPE ANODE DISCHARGE

A level-selective pumping in liquid edge-shape anode discharge can be done by resonance charge transfer. In this method of pumping, the ions acquire electrons in an upper laser state from neutral atoms or lower ionized species, rather than from free electron. Because the atomic process has a large cross-section, the charge transfer collisional laser can be operated at reduced density. Ionized species of charge Z created by electron-collisional ionization in the hot region of the plasma near the core of the column plasma can diffuse to the cooler plasma region near the liquid edge-shape anode, undergoing charge transfer collision with atoms, or lower ionized species. In this process, an electron is transferred from an atom or lower ionized specie into an ion of charge Z, thus a population inversion is created in the ion of charge state $Z-1$. In order to obtain large charge transfer rate, i.e., high density of population inversion, the ionization energy of atoms or lower ionized species have to closely match the energy difference between the ground state of specie Z and the selected laser upper level in specie $Z-1$.

Except the advantages and features mentioned above, the x-ray and/or EUV laser produced in accordance with the method and apparatus of the invention has a number of other special advantages, including: 1) liquid edge-shape anode is self-replenishing and self-healing, leading to stable liquid anode shape and a life time as long as liquid material is feed into the anode; 2) a large power x-ray and/or EUV laser consists of multi-liquid edge-shape anodes placed in a straight line can be operated in traveling-wave mode, leading to a large power, highly coherent x-ray and/or EUV laser.

The above and other advantages and features of the invention allow the inventive x-ray and/or EUV laser to be used in many applications, such as atomic physics and accelerators, electron spectroscopy for chemical analysis, diagnostics of high density fusion plasma, nuclear decay process, radiation chemistry, x-ray microscope and x-ray holography for biomedical sample, x-ray radiography and x-ray holography in nondestructive evaluation of material and structure.

Further features and advantages of the invention will become apparent from a study of following portions of the specification, the claims and the attached draws.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a generalized schematic diagram showing the method for generating x-ray and/or EUV laser in accordance with the present invention.

FIGS. 2A and 2B are schematic view of one embodiment of a apparatus for generating x-ray and/or EUV laser in accordance with the present invention.

FIG. 3A–FIG. 3C are schematic cross section views of three different embodiments for forming a liquid edge-shape anode in accordance with the present invention.

FIGS. 4A and 4B-FIGS. 6A and 6B are schematic views of alternative embodiments of a apparatus for generating x-ray and/or EUV laser in accordance with the present invention.

FIG. 7 is a schematic view of a x-ray and/or EUV laser with two mirrors in accordance with the present invention.

FIG. 8 is a schematic view of a large power x-ray and/or EUV laser consisting of multi-liquid edge-shape anodes placed in a straight line in accordance with the present invention.

DESCRIPTION OF PREFERRED EMBODIMENT

In describing the various embodiments of the invention, corresponding parts in different figures are designated with the same reference number in order to minimize repetitive description.

FIG. 1 is a schematic view illustrating the method for generating a x-ray and/or EUV laser in accordance with the present invention. A liquid edge 2 is electrically connected to a cathode 8 via a high voltage pulse power supply 10. Liquid edge 2 is set to be parallel to cathode 8, and both of them are disposed in vacuum. When high voltage pulse power supply 10 is turned on, a vacuum discharge will occur in a space between liquid edge 2 and cathode 8. The plasma will be confined into a high density and high temperature plasma column 4 in a space near liquid edge 2 by strong magnetic field induced by the huge discharge current. A population inversion in the confined plasma column will lead to a amplified simultaneous emission of x-ray and/or EUV 6 along the axis of plasma column 4.

FIG. 2A is a schematic view of one embodiment of the apparatus for generating x-ray and/or EUV laser in accordance with the present invention. A liquid edge-shape anode structure, described in detail in FIGS. 3A–3D, includes a edge-shape anode 20, a liquid material 16, a heater 18, a transmission line 12, and a reservoir 14 for supplying liquid material 16 to the end of edge-shape anode 20. FIG. 2B shows an enlarged view of the end of edge-shape anode 20. Liquid material 16 is most preferably made of material specifically selected for the generation of a plasma. For example, if an electron-collisional laser is to be constructed to produce laser radiation at the 23.2 nm of $3p$–$3s$ lasing line of Neon-like Ge^{22+}, liquid material can be made of Germanium. By way of further example, B_{60}-Ni_{13}-Pt_{27} eutectic can be used as such a liquid material, especially in the case where laser action is to be achieved in Boron ions. By way of still a further example, if a recombination laser is to be constructed to produce laser radiation at the 12.9 nm of $4f$–$3d$ line of Si^{11+}, liquid material can be made of Au_{69}-Si_{31} eutectic. Here, high Z gold atom can enhance radiative losses to rapidly cool the plasma. Preferably, the selected liquid material has a relatively low vapor pressure at their melting point, for example, lower than 10^{-4} Torr. Edge-shape anode 20 has a melting point higher than that of liquid material 16 and is substantially unreactive with liquid material 16 at the melting point of liquid material 16. Materials suitable for making edge-shape anode 20 include: Tungsten, Tantalum, Molybdenum, Nickel, Titanium, Platinum, Titanium carbide, Zirconium carbide, Boron nitride, Titanium boride, and BN-TiB_2 composite. Desirably, edge-shape anode 20 has an end with an apex radius in the range from 0.1 μm to 1,000 μm.

A heating filament 18 is provided adjacent to reservoir 14 such that a material of the specified type in solid phase during normal operation temperature of the x-ray laser may be placed in reservoir 14 and liquefied by heating filament 18. A heating power supply 30 provides a sufficiently heating current to heating filament 18. Heating filament 18 has the same potential as transmission line 12 and edge-shape anode 20.

Cathode 8, made of a metal or alloy conductor, preferably Copper because of its high electrical conductivity, is spaced apart and isolated from liquid edge-shape anode 20.

In laser operation, all elements described above are disposed in a vacuum chamber (not shown in FIGS. 2A and 2B), preferably, the vacuum pressure is lower than 10^{-6} Torr. A gas containing heavy atoms (high Z atoms) can be introduced into the vacuum chamber in order to rapidly cool plasma in electron-ion recombination excitation by radiative loss effect of heavy atoms.

Low impedance transmission line 12 and cathode 8 are connected to a capacitor 26, a capacitor 28 and a spark gap switch 22. First, capacitor 26 is charged to a potential not higher than threshold of vacuum discharge, usually this threshold is in the range of 10 kV to 20 kV. At this potential range, edge-shape anode 20 wet by liquid material 16 will form liquid edge 2 at its end in balancing between electrostatic and surface tension forces. The formed liquid edge 2 is called the Taylor cone, and usually has a apex radius smaller than 1 μm. This provides a sharp liquid edge suitable for generating a position stable, and uniform column plasma. Then capacitor 28 is charged to a potential at least higher than threshold of vacuum discharge. In order to provide large discharge current or high power necessary to generate x-ray laser, the capacitance of capacitor 28 should be sufficiently large, and the impedance of capacitor 28 and transmission line 12 should be very low. Connections among transmission line 12, capacitor 28, spark gap switch 22 and cathode 8 should be carefully done. When capacitor 28 is charged, a pulse from a high voltage trigger generator 24 turns on spark gap switch 22 and charges transmission line 12. At the same time, capacitor 26 will also be charged, which dilute the charging power to transmission line 12. So that the capacitance of capacitor 26 should be selected much smaller than that of capacitor 28. When transmission line 12 has been charged by capacitor 28, a vacuum discharge will occur in a space between liquid edge-shape anode 20 and cathode 8. Plasma column 4 will form in the space near liquid edge 2 by the confinement of strong magnetic field induced by the discharge current. X-ray and/or EUV laser will emit from plasma column 4.

FIG. 3A shows schematic cross section view of one embodiment of a liquid edge-shape anode structure in

accordance with the present invention. A supply of liquid material 16 is stored in a reservoir 14 having a trough-shape opening 34 with a width wider than the thickness of edge-shape anode 20 disposed in reservoir 14 and projecting through trough-shape opening 34.

Reservoir 14 is made of a material, preferably Tungsten, having a melting point higher than that of liquid material 16. Liquid material 16 is most preferably made of material specifically selected for the generation of a laser, mentioned in FIG. 2A. The requirements for edge-shape anode 20 have been also described in FIG. 2A. Heating filament 18 is provided adjacent to reservoir 14 such that a material of the specified type in solid phase during normal operation temperature of the x-ray laser may be placed in reservoir 14 and liquefied by heating filament 18.

FIG. 3B is an alternative embodiment for forming a liquid edge-shape anode structure in accordance with the present invention. The embodiment of FIG. 3B is similar to that of FIG. 3A except that a trough-shape neck 32 with a narrow chink is used as the edge-shape anode to supply liquid material 16 for forming liquid edge 2. Trough-shape neck 32 comprises a material, preferably Tungsten, having a melting point higher than that of liquid material 16. Trough-shape neck 32 does not react with but is wetted by liquid material 16. The width of chink of neck 32 is in the range from 0.1 μm to 1000 μm.

FIG. 3C illustrates yet another alternative embodiment for forming a liquid edge-shape anode structure in accordance with the present invention. A chamber housing 36 has a trough-shape opening 37 at its bottom where a edge-shape anode 38 is placed. Edge-shape anode 38 comprises a molded sintered metal or alloy selected from the materials for edge-shape anode 20 listed above in the description of FIG. 2A. Sintered edge-shape anode 38 has a porosity capable of feeding the liquid material through its body. Chamber 36 comprises a material, preferably Tungsten, having a melting point higher than that of liquid material 16 and is substantially unreactive with liquid material 16.

FIGS. 4A and 4B are an alternative embodiment of the apparatus for generating x-ray and/or EUV laser in accordance with the present invention. The embodiment of FIGS. 4A and 4B is similar to that of FIGS. 2A and 2B except that flat cathode 8 is replaced by an edge-shape cathode 40. This will form a better electrical field for focusing discharge current in the small space around liquid edge 2, thus increasing plasma density, uniformity and position stability.

FIGS. 5A and 5B are a further embodiment of the apparatus for generating x-ray and/or EUV laser in accordance with the present invention. The embodiment of FIGS. 5A and 5B are similar to that of FIGS. 2A and 2B except that cathode 8 is replaced by a cathode 44 and a trigger electrode 48. Trigger electrode 48 is insulated from cathode 44 by two insulating plates 46. First, capacitor 28 with large capacitance is charged to a high voltage which is not higher than vacuum discharge threshold. On this voltage, edge-shape anode 20 wet by liquid material 16 will form liquid edge 2. Then a capacitor 42 is charged to a high voltage which is higher than vacuum discharge threshold. When capacitor 42 has been charged, a pulse from high voltage trigger generator 24 turns on spark gap switch 22 therefore cause the first vacuum discharge in the space between trigger electrode 48 and liquid edge-shape anode 20. This vacuum discharge will trigger the second vacuum discharge with huge current between cathode 44 and liquid edge-shape anode 20 through capacitor 28, thus column plasma 4 is produced by the confinement of strong magnetic field induced by this huge discharge current. The advantage of this embodiment is that final discharge current is not limited by capacity of spark gap switch 22 as in FIG. 2A. This embodiment is useful when a relatively huge discharge current is needed.

FIGS. 6A and 6B show still a further embodiment of the apparatus for generating x-ray and/or EUV laser in accordance with the present invention. The embodiment of FIGS. 6A and 6B is similar to that of FIGS. 2A and 2B except that the discharge is triggered by a focused laser beam 52. First, capacitor 28 is charged to a high voltage which is not higher than vacuum discharge threshold. Then a conventional laser beam 52 is focused to liquid edge 2 by an optical lens system 54. Focused laser beam 52 will evaporate liquid material 16 in liquid edge 2, which will trigger vacuum discharge in the space between a cathode 50 and liquid edge-shape anode 20. Column plasma 4 will form in the space near liquid edge 2 by the confinement of strong magnetic field induced by the huge discharge current, and x-ray and/or EUV laser 6 will emit from column plasma 4.

An optical resonator, constituted by two or more reflecting surfaces can be implemented to enhance the amplification of x-ray and/or EUV laser. FIG. 7 shows an embodiment of a x-ray and/or EUV laser with two mirrors in accordance with the present invention. Lasing x-rays 6 from plasma column 4 are reflected by a mirror 56, partially reflected by a beam splitter 58, and output through splitter 58.

FIG. 8 shows an embodiment of a large power x-ray and/or EUV laser consisting of multi-liquid edge-shape anodes placed in a straight line in accordance with the present invention. N liquid edge-shape anodes are placed in a straight line and operated in a traveling-wave mode. Each liquid edge-shape anode is driven by one pulse power supply 10. There is a time delay between two current pulses delivered to any adjacent liquid edge-shape anodes. The time delay is equal to the distance between corresponding liquid edge-shape anodes divided by the velocity of light. In this way, the X-ray lasing emission in one plasma column is stimulated by X-ray beam lased from the former plasma column. So that X-ray laser is amplified when passing each plasma column. The advantage of this new concept laser is no reflective mirror, i.e. no mirror reflection loss happened as in the conventional resonators. This will significantly increase the efficiency and power of X-ray laser, especially in x-ray wavelength range because of lack of qualified x-ray mirrors. Next, let us consider the output power of the multi-column X-ray laser.

Assuming the gain-length product, GL, to be the same for each plasma column, the X-ray laser power after each plasma column can be written as,

First plasma column:
$$I_1 = S(e^{GL} - 1) \quad (1)$$

where, S is a constant.

Second plasma column:
$$I_1 e^{GL} < I_2 < I_1(1 + e^{GL}) = I_2' \quad (2)$$

Third plasma column:
$$I_1 e^{2GL} < I_3 < I_2' + I_1(e^{GL})^2 = I_1(1 + e^{GL} + e^{2GL}) = I_3' \quad (3)$$

N-th plasma column:
$$I_1 e^{(N-1)GL} < I_N < I_{N-1}' + I_1(e^{GL})^{N-1} = \quad (4)$$

-continued

$$I_1(1 + e^{GL} + e^{2GL} + \ldots + e^{(N-1)GL})$$

where, the left side of the i-th equation is the case assuming that the X-ray emitted from plasma column (i−1) only stimulates the plasma column (i) and disperses before reaching plasma column (i+1), and the right side of the i-th equation is the case assuming that the X-ray emitted from plasma column (i−1) stimulates all plasma column after column (i−1), i.e. no beam dispersion. For a gain-length product GL=2, 3; N=3, 5, 7, the ratio of the x-ray laser power output of the N-th plasma column to that of the first plasma column is calculated as shown in Table I.

TABLE I

N	Calculated laser power output GL = 2	GL = 3
3	$5.4 \times 10^1 \sim 6.30 \times 10^1$	$4.03 \times 10^2 \sim 4.25 \times 10^2$
5	$2.98 \times 10^3 \sim 3.45 \times 10^3$	$1.63 \times 10^5 \sim 1.71 \times 10^5$
7	$1.63 \times 10^5 \sim 1.88 \times 10^5$	$6.57 \times 10^7 \sim 6.91 \times 10^7$

From the above table, we can see that a extremely large power X-ray laser can be built by using the multi-plasma-column x-ray laser.

FIG. 8 also shows the power supply system for driving multi-plasma-column x-ray laser. Each x-ray laser is driven by one pulse power supply 10. All power supplies are triggered by one trigger generator 24 through the lines with different lengths. The length difference between the two lines of any two column x-ray lasers is set to be equal to the distance between the corresponding two column x-ray lasers. In this way, multi-plasma-column x-ray laser can be operated in traveling-wave mode.

Similar to the trigger method described in FIGS. 6A and 6B, the multi-plasma-column x-ray laser also can be triggered by multi-laser-beams, each of which delivers one pulse laser beam to evaporate the liquid material on each liquid edge-shape anode in a time sequence, time interval between two adjacent pulse laser beam is set to be equal to the distance between the corresponding adjacent liquid edge-shape anodes divided by the velocity of light.

It is to be understood that embodiments described herein are merely illustrative of the principle of the invention. Various modifications and changes may be made thereto by persons skilled in the art which will embody the principle of the invention and fall within the spirit and scope thereof.

What is claimed is:

1. An apparatus for producing x-ray and/or EUV laser comprising:

(1) a liquid edge-shape anode structure including: a liquid material, a reservoir for holding said liquid material, said reservoir having a trough-shape opening for passage of said liquid material, and liquid material feeding and liquid edge forming means operatively associated with said reservoir for feeding liquid material through the trough-shape opening in said reservoir and for forming a liquid edge from said liquid material;

(2) a cathode electrode opposite said liquid edge-shape anode;

(3) pulse power supply and electrical discharge circuit having a low impedance circuit configuration for providing a sufficient large current pulse passing through said liquid edge-shape anode and said cathode, which generates both a plasma and a magnetic field which helps confine said plasma to a thin column, said confined thin plasma column emits x-ray and/or ultraviolet laser.

2. The apparatus of claim 1 wherein said liquid material feeding and liquid edge forming means comprises a trough-shape neck with a narrow chink connected to said trough-shape opening for communicating with said reservoir, the liquid material passing through the narrow chink in said trough-shape neck and forming a liquid edge at the end of said trough-shape neck, said trough-shape neck being made of material having a melting point higher than that of said liquid material and substantially unreactive with said liquid material at the melting point of said liquid material.

3. The apparatus of claim 1 wherein said liquid material feeding and liquid edge forming means comprises an element having a edge-shape end, being made of a porous, sintered metal or metal alloy and communicating with the liquid material by the opening in said reservoir, the liquid material passing through said element and forming a liquid edge at the edge-shape end of said element.

4. The apparatus of claim 1 wherein said liquid material feeding and liquid edge forming means comprises a solid plate having a edge-shape end, being disposed in said reservoir and projecting through said opening, the liquid material wetting and flowing on the surfaces of said solid plate and forming a liquid edge at the edge-shape end of said solid plate, said solid plate being made of material having a melting point higher than that of said liquid material and substantially unreactive with said liquid material at the melting point of said liquid material.

5. The apparatus of claim 1 wherein said liquid material contains an atomic element which radiates laser light produced by said apparatus.

6. The apparatus of claim 5 wherein said liquid material further contains a heavy atomic element which is capable of providing a large radiation cooling rate for the plasma column produced by said apparatus.

7. The apparatus of claim 1 which further comprises environment of a gas of a heavy atom which is capable of providing a large radiation cooling rate for the plasma column produced by said apparatus.

8. The apparatus of claim 1 wherein said cathode is planar.

9. The apparatus of claim 1 wherein said cathode is shaped in the form of an edge.

10. The apparatus of claim 1 wherein said cathode comprises a trigger electrode for triggering discharge, and a main electrode for passing discharge current, said trigger electrode being electrically isolated from said main electrode by insulators.

11. The apparatus of claim 1 wherein said pulse power supply and electrical discharge circuit comprise capacitors, a spark gap switch, a trigger generator, and transmission lines.

12. The apparatus of claim 1 wherein said liquid edge-shape anode structure further comprises a heating means for heating said liquid material which is in solid phase during normal operation temperature of said apparatus.

13. The apparatus of claim 1 which further comprises a reflecting mirror located at one end of axis of said plasma column for reflecting laser radiation through said plasma column, and a partially reflected beam splitter located at the other end of axis of said plasma col-

umn for reflecting laser radiation through said plasma column and outputting laser radiation.

14. The apparatus of claim 1 which further comprises a conventional laser system being capable to deliver an optical laser pulse onto said liquid edge for evaporating the liquid material on said liquid edge, which triggers a vacuum discharge between said liquid edge-shape anode and said cathode.

15. A method for producing x-ray and/or EUV laser comprising:

(1) providing an anode means having a liquid edge;

(2) providing a cathode electrode opposite said liquid edge;

(3) providing a pulse power supply and electrical discharge circuit having a low impedance circuit configuration for providing a sufficient large current pulse passing through said anode means and said cathode, which generates both a plasma and a magnetic field which helps confine said plasma to a thin column, a population inversion is created in said plasma column which results in emission of x-ray and/or ultraviolet laser.

16. The method of claim 15 wherein the inducing of the plasma process that generates the population inversion is by means of plasma inducing process selected from the group comprising electron-collisional excitation, electron-ion recombination, photoexcitation, photoionization, and charge transfer.

17. The method of claim 15 wherein the inducing of the plasma process that generates the population inversion is by means of electron-ion recombination and the plasma cools at a termination of a current pulse following electron heat conduction to said liquid edge.

18. The method of claim 15 wherein the inducing of the plasma process that generates the population inversion is by means of electron-ion recombination and the plasma cools by radiation from a highly ionized material.

19. The method of claim 15 wherein the plasma process that generates the population inversion is electron-ion recombination and laser results from a population inversion in a hydrogenic ion.

20. The method of claim 15 wherein the plasma process that generates the population inversion is electron-ion recombination and laser results from a population inversion in a helium-like ion.

21. The method of claim 15 wherein the plasma process that generates the population inversion is electron-ion recombination and laser results from a population inversion in a lithium-like ion.

22. The method of claim 15 wherein the plasma process that generates the population inversion is electron-collisional excitation and laser results from a population inversion in a nickel-like ion.

23. The method of claim 15 wherein the plasma process that generates the population inversion is electron-collisional excitation and laser results from a population inversion in a neon-like ion.

24. The method of claim 15 wherein the radiation from said plasma column produces x-ray and/or EUV laser action by photoexcitation.

25. The method of claim 15 wherein the radiation from said plasma column produces x-ray and/or EUV laser action by photoionization.

26. The method of claim 15 wherein the radiation from said plasma column produces x-ray and/or EUV laser action by charge transfer.

27. The method of claim 15 wherein said plasma column has a hot plasma part near the core of said plasma column, x-ray or EUV radiation from said hot plasma part excites or ionizes lower ionized atoms, or atoms from different species in cooler plasma part that close to said liquid edge-shape anode, thus the laser action in the cooler plasma part is created.

28. The method of claim 15 wherein said plasma column has a cooler plasma part near said liquid edge, diffusion of ions from the hot plasma part into the cooler plasma part creates the laser action.

29. An apparatus for producing large power x-ray and/or EUV laser comprising:

(1) multi-liquid edge-shape anodes placed in a straight line; each liquid edge-shape anode including: a liquid material, a reservoir for holding said liquid material, said reservoir having a trough-shape opening for passage of said liquid material, and liquid material feeding and liquid edge forming means operatively associated with said reservoir for feeding liquid material through the trough-shape opening in said reservoir and for forming a liquid edge from said liquid material;

(2) a cathode electrode opposite said multi-liquid edge-shape anodes;

(3) multi-pulse power supplies and electrical discharge circuits, each pulse power supply and electrical discharge circuit having a low impedance circuit configuration for providing a sufficient large current pulse passing through one liquid edge-shape anode and said cathode, which generates both a plasma and a magnetic field which helps confine the plasma to a thin column, said confined thin plasma column emits x-ray and/or ultraviolet laser, there is a time delay between two current pulses delivered to any adjacent liquid edge-shape anodes, and said time delay is equal to distance between corresponding adjacent liquid edge-shape anodes divided by the velocity of light.

30. The apparatus of claim 29 wherein said multi-pulse power supplies are triggered by one trigger generator through lines with different lengths, the length difference between two adjacent lines is set to be equal to the distance between corresponding adjacent liquid edge-shape anodes.

31. The apparatus of claim 29 wherein said multi-pulse power supplies are triggered by multi-laser-beams, each of which delivers one pulse laser beam to evaporate liquid material on each liquid edge in a time sequence, time interval between two adjacent pulse laser beams is set to be equal to the distance between corresponding adjacent liquid edge-shape anodes divided by the velocity of light.

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[54] LASER SYNCHROTRON SOURCE (LSS)

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Primary Examiner—Léon Scott, Jr.

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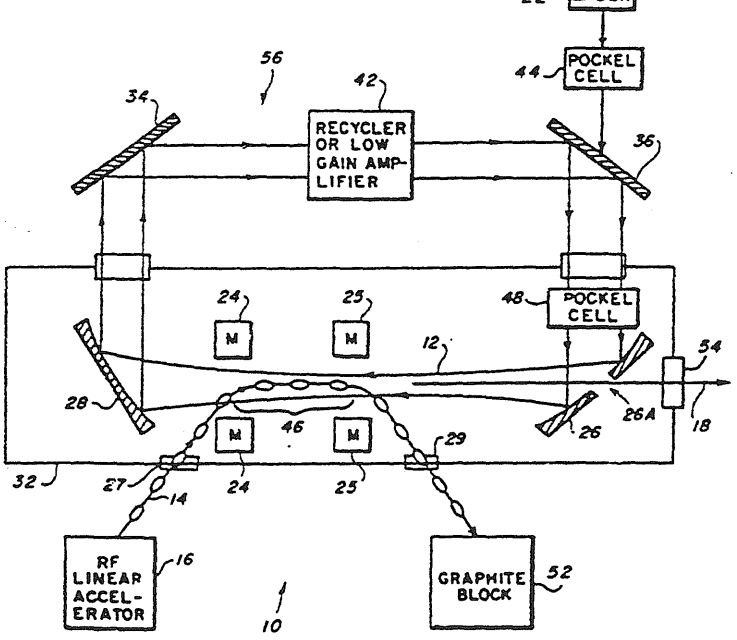
[57] ABSTRACT

The laser synchrotron source (LSS) utilizes a high peak power or high average power laser to generate within a vacuum chamber a laser beam traveling in one direction to interact with an electron beam traveling in an opposite direction in order to generate high-power x-rays. A ring resonator formed by a plurality of mirrors directs the laser beam in a closed loop to impact with the electron beam to produce x-rays. Concave mirrors in the ring resonator focus the laser beam upon the point where the laser beam interacts with the electron beam to intensify the laser energy at that point. When a radio frequency linear accelerator (rf linac) is used to produce the electron beam, x-rays having a short pulse length are generated. When a betatron is used as an electron source, x-rays having a long pulse length are generated.

33 Claims, 2 Drawing Sheets



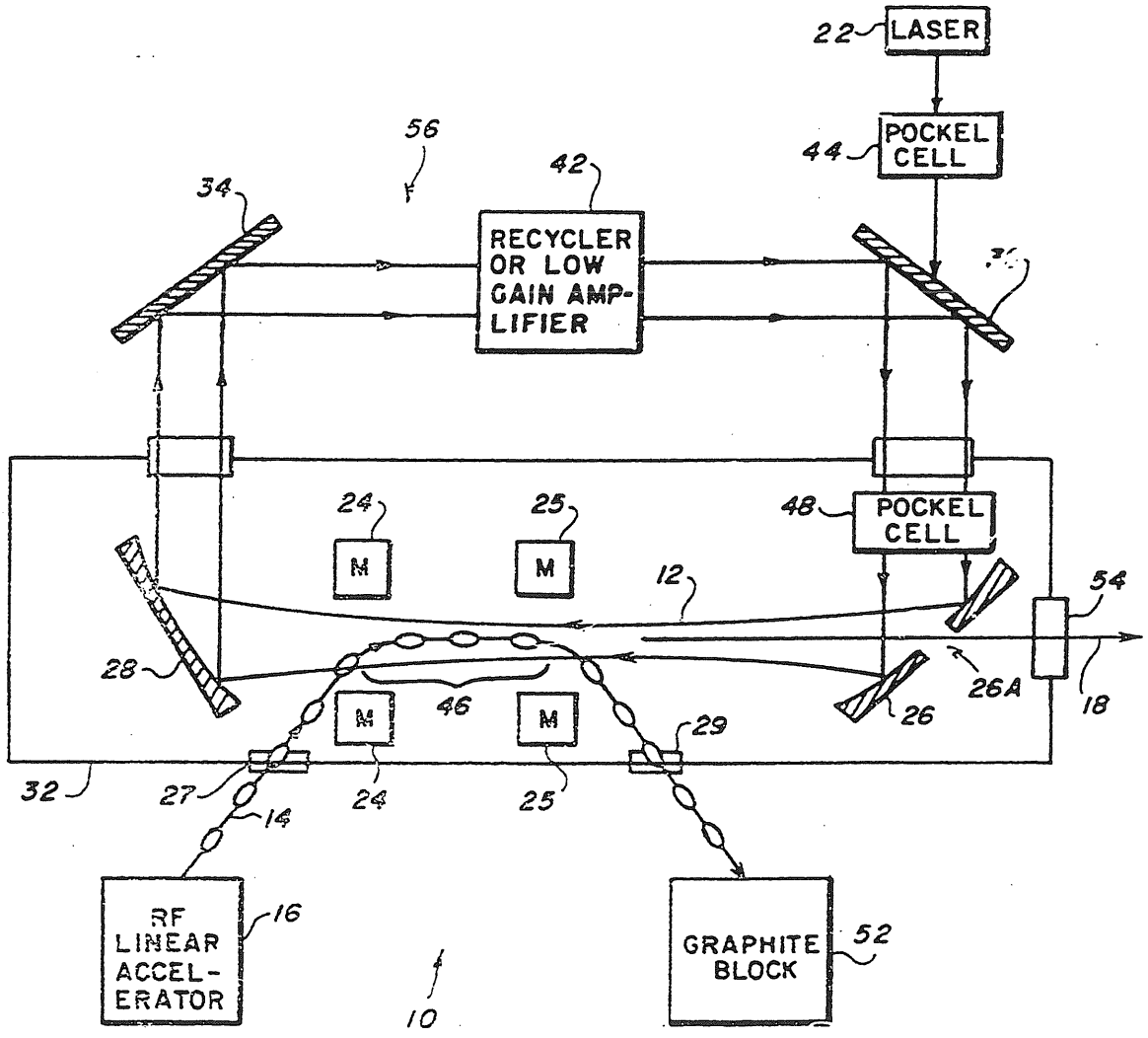

22
LASER
44
POCKEL CELL
56
42
34
RECYCLER OR LOW GAIN AMP-LIFIER
36
24
25
48
POCKEL CELL
M
M
12
54
28
46
26A
18
M
M
29
26
32
27
24
25
14
RF LINEAR ACCEL-ERATOR
16
GRAPHITE BLOCK
52
10

FIG. 1

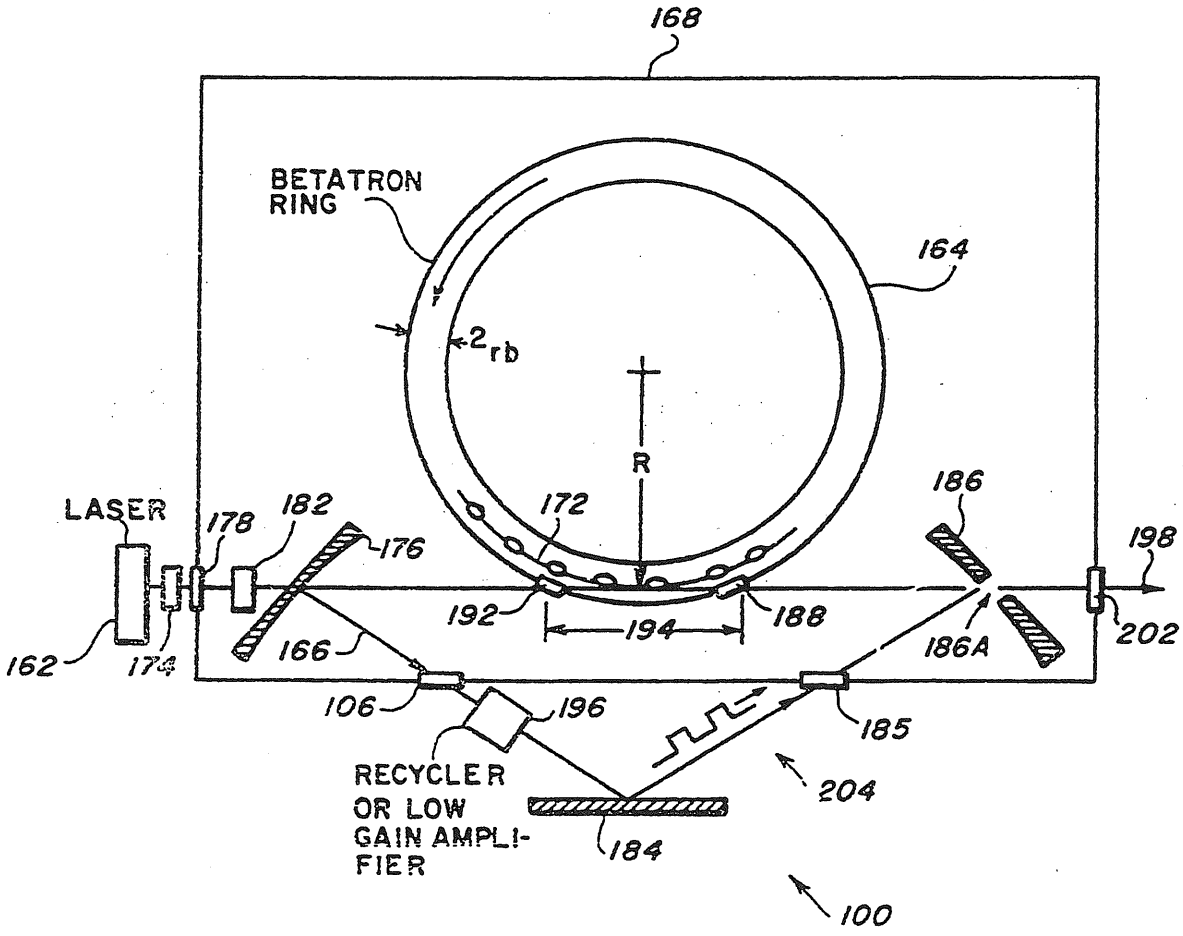

168
BETATRON RING
164
$2r_b$
R
LASER
178
182
176
172
186
198
162
174
166
192
194
188
186A
202
106
196
185
RECYCLER OR LOW GAIN AMPLI-FIER
184
204
100

FIG. 2

LASER SYNCHROTRON SOURCE (LSS)

BACKGROUND OF THE INVENTION

1. Field of the Invention

The Laser Synchrotron Source (LSS) is a compact source of short-pulse, coherent or incoherent (near monochromatic), tunable, hard x-rays.

2. Description of the Related Art

Conventional x-ray sources rely on either the Bremsstrahlung radiation produced when energetic electrons are decelerated by high Z (atomic number) materials in common x-ray tubes, or synchrotron radiation produced by ultrahigh energy electron beams passing through magnetic undulators or dipoles in a Storage Ring Synchrotron Source (SRSS).

The x-rays produced in common x-ray tubes (Bremsstrahlung) have the undesirable properties of low power, long-pulses or continuous wave (CW), broadband, uncollimated, line spectra confined to atomic transitions and hence not tunable, unpolarized, and incoherent radiation.

The SRSS also have a number of unfavorable features and characteristics. Such sources require highly energetic electron beams, typically many GeVs which in turn require large and expensive facilities. The x-ray radiation generated by the SRSS has relatively long duration (>100 ps) pulses, broadband, incoherent, low energy (<50 keV), fixed polarization, not tunable and incapable of frequency chirping.

SUMMARY OF THE INVENTION

One object of the laser synchrotron source (LSS) is to provide a device for achieving intense hard x-ray production having ultra-short pulses and extremely high peak power utilizing an ultra-high intensity laser whose polarization and chirping can be controlled.

Another object of the LSS is to provide an x-ray source that is compact, requires low power and limited radiation shielding.

The LSS is comprised of a high peak power or high average power laser to generate a laser beam which produces x-rays upon interacting with an electron beam in a vacuum environment. The electron beam is generated by either a radio frequency linear accelerator or betatron. A multiple of mirrors forming a ring resonator reflect the laser beam in a continuous loop so that it may be reused over and over again. The energy in the laser beam is replenished by being recycled in an amplifier circuit to replace the energy lost through scattering and diffraction at the mirrors and upon impact with the electron beam.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram showing a laser synchrotron source (LSS) utilizing a Radio Frequency Linear Accelerator (rf linac) to generate an electron beam.

FIG. 2 is a schematic showing a Laser Synchrotron Source (LSS) utilizing a betatron to generate an electron beam.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The laser synchrotron source (LSS) produces a laser beam and an electron beam which interact to generate

In the preferred embodiment, FIG. 1, the laser source 22 is a high peak power laser; alternatively, a high average power laser, i.e., a solid state laser, such as a high power modified Nd:YAG laser or equivalent, may be used.

The preferred laser 22 is a Table-Top Terawatt (T^3) laser system manufactured by Positive Light of Los Gatos, CA, wherein a low energy pulse from an ultra-short pulse, mode-locked oscillator is temporally stretched, amplified, and recompressed by the chirped pulse amplification (CPA) technique to produce a ~1 psec laser pulse with peak laser power in the 1-10 TW power range. T^3 lasers can be repetition rated (reprated) up to ~1 kHz at the ~1 TW level. Any high peak power laser, other than a T^3, may be utilized. High peak power lasers, however, are commonly located in large laser facilities such as Lawrence Livermore National Laboratories, Livermore, CA. However, these large lasers do not perform the desired function of being capable of utilization in a small laboratory facility.

It is essential that the x-ray beam generated by the interaction of the laser beam 12 be coherent as opposed to incoherent. In the coherent x-ray beam, the radiation of the laser beam 12 is very intense, very directional and its frequency content is very pure. In the incoherent x-ray beam, there is a broadband spectrum and some of the optical properties found are undesirable. However, as a general matter the x-rays within an LSS x-ray beam 18 are in both coherent and incoherent states and the state selected for operation depends upon the parameters selected for operation of the LSS. If proper parameters are not present within the system, incoherent x-rays will be emitted. To achieve the coherent state, the parameters of the laser must be properly tuned so that the laser beam 12 and the electron beam 14 will intensely interact and produce a coherent x-ray beam 18.

A relatively low energy (<100 MeV) Radio-Frequency Linear Accelerator (rf linac) 16, or cyclic electron (betatron) source, producing an electron beam and the sub-picosecond laser pulses from the T^3 laser system 22 propagate in opposite directions to each other. Intense x-ray radiation 18 is produced by linear and nonlinear Thomson scattering of the laser radiation off the energetic electrons. In addition, coherent x-ray radiation 18 may also be generated by self-amplification of the spontaneous (Thomson radiation) through the free electron laser (FEL) mechanism. Operation at harmonics of the doppler upshifted laser frequency can be achieved by increasing the intensity of the incident laser field .

The production of intense hard x-rays 18 is achieved as a result of the ultra-high intensity of the laser radiation from the T^3 laser system 22 interacting with the electron beam 14. The T^3 laser can generate a laser intensity in excess of 10^{18} W/cm^2 where electron motion in the laser radiation field can become relativistic. This creates new regimes of interaction unattainable by any existing or proposed x-ray generation schemes. Extremely high energy (~10 keV-~1000 keV) x-rays 18 can be generated as either the fundamental or the harmonics of the doppler upshifted laser radiation using an electron beam 14 or a cold, high density plasma.

Ultra-short pulses of x-rays 18 can be generated. The upper limit of the pulse length is determined by the shortest micropulse structure available for the electron beam 14, which is ~1 ps (10^{-12} sec). Shorter x-ray pulses 18 can be achieved by having the electron beam

limit of the pulse length is set by the shortest pulse attainable for the T^3 laser 22 pulse.

The intense radiation from the T^3 laser system 22 can act as an electromagnetic wiggler for the electron beam 14, and coherent x-ray 18 radiation can be produced through the laser pumped FEL mechanism. Because of the ultra-intense and short pulses from the T^3 laser 22, x-rays produced in the LSS 10 have extremely high peak power.

As stated above, picosecond x-ray pulses 18 are generated by interacting a high peak power laser beam 12 with a picosecond micropulse electron beam 14 from an rf linac 16. The beam generated by the laser 22 enters the ring resonator or ring resonator circuit 56 formed by two mirrors 26 and 28 located within a vacuum or interaction chamber 32, and two mirrors 34 and 36 preferably located outside of the interaction or vacuum chamber 32 reflect the laser beam 12 in a closed loop.

The mirrors 26, 28, 34 and 36 are all standard optical mirrors. Mirrors 34, and 36 are high power dielectric mirrors. Mirrors 26 and 28 are off-axis parabaloid concave mirrors to focus the laser beam 12 as it interacts with the electron beam 14 which increases the intensity of the laser beam 12. Window 26A is constructed of beryllium to allow the passage of the x-rays generated when this constricted laser beam 12 strikes the electron beam 14.

The laser beam 12 is gated by using such optical devices as Pockel cells 44 and 48 to change the polarization of the laser beam 12. Each cell 44 and 48 acts like a gate that can open and shut, allow the pulses from the laser 22 to enter into the ring resonator, or ring resonator circuit, 56 through the mirror 36 in a first polarized state. After passing through mirror 36, the laser beam 12 is rotated by Pockel cell 48 to an opposing polarization. The laser beam 12, upon striking mirror 36 on subsequent passages, is prevented from exiting the ring resonator 56 by virtue of the opposite polarization of the laser beam 12 while in the ring resonator 56.

The electron beam 14 from the rf linac 16 enters the vacuum or interaction chamber 32 through a vacuum port 27 and upon entering the path of the laser beam 12 is bent by magnets (M) 24 so as to travel in an opposite direction parallel to the path of the laser beam 12. The relativistic electron beam interacting with the incident counterstreaming laser beam emits synchrotron radiation, or x-rays 18. The emitted x-rays 18 exit the vacuum chamber 32 through a window 54 to impact upon a target surface (not shown) for application. After interacting with the laser beam 12, the electron beam 14 is then bent by magnets (M) 25 so as to exit the interaction chamber through a vacuum port 29 where it can either be recycled in the rf linac 16 or disposed of in a graphite block 52.

The output of the rep-rated rf linac 16 consists of a series of micropulses and macropulses. In typical rf linacs 16, the micropulse time (τ_m) is $\tau_m = L_b/c \simeq 10$ psec and the macropulse is $T_m \simeq 20$ μsec. The micropulse (f_m) and macropulse (F^m) rep-rate is micropulse time (τ_m) is $\tau_m = L_b/c \simeq 10$ psec and the macropulse is $T_m \simeq 20$ μsec. The micropulse (f_m) and macropulse (F^m) rep-rate is typically $f_m \simeq 3$ GHz and $F_m \simeq 100$ Hz. The separation of the series of micropulses is $\Delta T_m = 1/f_m \simeq 350$ psec, and the overall duty factor for the full electron beam 14 pulse train is $D = F_m f_m T_m \tau_m \simeq 6 \times 10^{-5}$. Due to the relatively low duty factor ($D = 0.1^{-5}$) associated with rf linacs 16, a rep-rated LSS 10 requires a laser 22 system that has high average power.

After interacting with the electron beam 14, the laser beam 12 is reflected outside of the interaction chamber 32 by mirrors 28 and 34 into either a high energy recycler (for a high peak power laser) where the beam is stretched amplified and recompressed or a low gain amplifier 42 (for a high average power laser) where the beam is amplified, to compensate for any losses due to scattering or diffraction as the result of the operation of the mirrors and impinging the electron beam. The rejuvenated laser beam 12 is then reflected by mirror 36 back into the ring resonator circuit 56.

It is implicitly assumed in the LSS generation of x-rays 18 that all the electrons in the micropulse are acted upon by approximately the same incident laser field amplitude. This requires that the electron beam 14 micropulse length be somewhat less than the laser 22 Rayleigh length, i.e., $L_b < Z_R$, where L_b is pulse length and Z_R is Rayleigh length. To maintain a uniform high efficiency operation the spot size of the incident laser beam 12 should be somewhat larger than the electron beam 14 radius, i.e., $r_o > r_b$, where r_o is spot size and r_b is beam radius.

Slippage between the x-ray pulse le and the electron micropulse 14 is negligibly small compared to the electron micropulse 14 length. Hence, the x-ray pulse le structure is essentially identical to that of the electron beam pulse structure, i.e., psec electron pulses 14 generate psec x-ray pulses le. Both the electron beam 14 and x-ray pulse 18 are overlapped and travel together at nearly the velocity of light through the counterstreaming incident laser pulse 12. Ultra-short x-ray pulses 18 ($\sim$ psec) can also be generated using long electron pulses 14 ($>>$psec).

Nominally a pulsed laser configuration rep-rated at the frequency of electron micropulses is employed. The laser pulse train is arranged to circulate in a ring resonator 56 configuration with an optical path length which is an integral multiple of ΔT_m, the separation of the micropulses. The electron beam 14 micropulses are brought into one arm of the laser resonator with a turning magnet 24 and synchronized with the laser 12 pulses so that they interact with each other in the vicinity of the focal point 46. Synchronization between the laser 12 pulses and electron beam 14 pulses is achieved by vicinity of the focal point 46. Synchronization between the laser 12 pulses and electron beam 14 pulses is achieved by driving the laser mode-locked oscillator (not shown) at subharmonics of the master oscillator signal (not shown) of the rf linac 16.

Synchronization between the single laser pulse 12 and the rf linac 16 electron beam 14 is achieved with a laser-triggered photocathode (not shown) at the beam injector (not shown) of the rf linac 16. Part of the laser beam pulse 12 from the T^3 laser 22 is diverted to illuminate the photocathode (not shown) of the rf linac 16. Table I shows the required parameters for a high peak power LSS 10 using a rf linac 16 to generate psec x-ray pulses 18 having 6×10^9 photons/pulses.

In a second preferred embodiment 100, FIG. 2, utilizes either a T^3 laser 162 or a solid state laser, as discussed above, as the source of a laser beam 166, and a betatron 164 as the source of an electron beam 172.

When utilizing the betatron 164 as an electron source, the ring resonator or ring resonator circuit 204 is comprised of three mirrors 176, 184 and 186 (having similar characteristics to the mirrors previously discussed) arranged in a triangular mirror configuration. However, the triangular configuration is immaterial, the configu-

ration of the mirror may assume a plurality of mirrors.

TABLE I

High Peak Power Laser Synchrotron Source Using an RF Linac

Incident Laser Parameters	
Wavelength, λ_o	1 μm
Energy/Pulse, E_o	20 J
Peak Power, P_o	10 TW
Laser Pulse Length, L_o/c	2 psec
Spot Size, r_o	50 μm
Rayleigh Length, Z_R	0.8 cm
Electron Pulse Parameters	
Beam Energy, E_b	50–250 MeV
Beam Current, I_b	200 A
Beam Pulse Length, L_b/c	1 psec
Beam Radius, r_b	50 μm
Beam Energy Spread $(\Delta E/E_b)_{int}$	0.5%
Beam Emittance, ϵ_n	5 mm-mrad
X-Ray Pulse Parameters	
Photon Energy E_p	50–1200 keV
Peak Photon Flux, F	6×10^{21} photons/sec(*)
Photon Pulse Length,, L_b/c	1 psec
Photons/Pulse, FL_b/c	6×10^9 photons/pulse(*)
Peak Brightness, B	6×10^{19}–1.5×10^{21}(+)
Angular Spread, $\Theta \sim 1/\gamma$	10^{-2} mrad

(*)Includes all photons within the $\sim 1/\mu$ angle, implying $\sim$100% BW.
(+)The unit for brightness is photons/sec-mm^3-mrad^2 (0.1% BW).

Mirrors 176 and 186 are off-axis parabaloid concave mirrors and mirror 186 has a beryllium window 186A to allow the passage outside of the interaction chamber 168 of the x-rays 198 generated by the interaction of electron beam 172 and a laser beam 166.

The laser beam 166 enters the ring resonator circuit from a laser source 162 through a laser window 178 and the mirror 176 after being gated by Pockel cells 174 and 182, as discussed in the first preferred embodiment, to prevent the laser beam 166 from escaping the ring resonator circuit 204 on subsequent passages. Mirror 176 reflects the laser beam 166 out of the interaction chamber 168 through a laser window 106 to a second mirror 184 after passing through either a recycler (in the case of a high peak power laser) or a low gain amplifier (in the case of a high average power laser) 196. The recycler or low gain amplifier 196 operates as previously described. Mirror 184 then reflects the laser beam 166 through laser window 185 to a third mirror 186 where the laser beam 166 is constricted and enters the betatron 164 through a first vacuum port 188 and impacts the electron beam 172. Upon the interaction of the laser beam 166 with the electron beam 172, x-rays 198 are emitted, as previously described. These x-rays 198 pass out of the vacuum chamber 168 through a window 202 for application as desired. The characteristics of the x-rays 198 generated utilizing the betatron are as previously described when utilizing a rf linac.

A conventional air core betatron 164 produces $\sim$100 A of circulating current at energies of $\sim$50 MeV. This betatron 164 is extremely compact, varying in radius from $\sim$4–24 cm. If a modified betatron 164, having additional stabilizing magnetic fields to stably confine and accelerate high currents, is used in the embodiment it will produce $>$1 kA at energies of $>$20 MeV. The beam radius of the modified betatron is 1 m.

The interaction distance L_{int} 194 is given by $L_{int} \simeq (2Rr_b)^{\frac{1}{2}}$, where R is the major radius of the betatron 164 and r_b is the horizontal radius of the electron beam 172. An average spectral brightness of $\sim 3 \times 10^{11}$ photons/sec-mm^{2}mrad^2(0.1% BW) at x-ray photon energy of 50 keV is obtained. Due to the CW nature of both the electron 172 and laser 166 beams, the duty factor is equal to 1. This leads to an increase of the average photon flux, when compared to the high average power LSS using an rf linac 196. Table II shows the parameters for a high average power LSS using a conventional betatron.

A wide range of wavelengths is available for the x-rays 198 generated by the LSS 100. For a fixed electron energy, discrete wavelengths at odd harmonics of the laser frequency are produced. These harmonics can be continuously tuned in frequency by adjusting the energy of the electron beam 172. Control of polarizations of the x-rays 198 with fast response times can be easily achieved by controlling the polarization of the laser 162.

TABLE II

High Average Power Laser Synchrotron Source Using a Conventional Betatron

Incident Laser Parameters	
Wavelength, λ_o	1 μm
Average Circulating Power, P_o	5 kW
Average Laser Amplifier Power P_{in}	100 W
Spot Size, r_o	50 μm
Rayleigh Length, Z_R	0.8 cm
Electron Pulse Parameters	
Beam Energy, E_b	50–250 MeV
Beam Current, I_b	100 A
Beam Major Radius, R	25 cm
Beam Cross-section, A_b	$\pi \times 50 \times 150$ μm^2
Interaction Distance, L	1.7 cm
Beam Energy Spread $(\Delta E/E_b)_{int}$	1%
X-Ray Pulse Parameters	
Photon Energy E_b	50–1200 keV
Average Photon Flux, <F>	3×10^{13} photons/sec(*)
Average Spectral Brightness, <B>	3×10^{11}–7.5×10^{12}(+)

(*)Includes all photons within the $\sim 1/\gamma$ angle, implying $\sim$100% BW.
(+)The unit for brightness is photons/sec-mm^2-mrad^2(0.1% BW).

The availability of elliptical (or circular) and linearly orthogonal polarizations would be crucial to many magnetic probing of matter experiments with x-rays.

By frequent chirping the laser pulse (which is inherent for a T^3 laser system that employs the chirped pulse amplification method), x-ray pulses with frequency chirping can be obtained from a LSS. Frequency chirping is very useful in material research using short pulse x-rays.

A LSS, as shown in the previously described embodiments, has several advantages. First, the cross-section of the x-ray source in a LSS is given by the overlap of the radiation spot size and electron beam size. This improves substantially the spatial coherence of the x-ray emitted from a LSS. Secondly, the apparatus comprising the LSS is compact and requires a space only tens of square meters as opposed to tens of thousands of square meters for the storage ring synchrotron source (SRSS) and the current generation of laser sources capable of generating high peak power laser pulses. Thirdly, the LSS has low power requirements as compared to other storage ring devices due to the much lower energy of the electron beams from rf linacs. Further, the LSS requires substantially less radiation shielding due to the lower energies of the electron beams. Lastly, high-density, low temperature plasma can also be used in place of an electron beam. In this case, only harmonics of the backscattered laser radiation will be produced.

The picosecond x-rays generated by the LSS are useful in materials studies for studying various chemical transitions in chemical reactions. In medical research, the longer x-rays generated utilizing the betatron are useful.

The design and operation of the LSS has been described in the papers by Sprangle et al., *Tunable, Short Pulse Hard X-Rays from a Compact Laser Synchrotron Source*, SSRL Workshop on Fourth Generation Light Sources, pp. 289–298, 24–27 Feb. 1992; Sprangle et al., *Tunable, Short Pulse Hard X-rays from a Compact Laser Synchrotron Source*, Naval Research Laboratory Report No. NRL/MR/4790-92-6963, Jul. 16, 1992; and Sudan, *A Note on a Tunable Source of Short [illegible] Rays*, ... published, Oct. 7, 1992; which are herein incorporated by reference.

Although the invention has been described in relation to exemplary embodiments thereof, it will be understood by those skilled in this art that still other variations and modifications can be affected in these preferred embodiments without detracting from the scope and spirit of the invention. The limits on this invention are as described in the claims.

What is claimed is:

1. A device comprised of:
means for generating a tunable laser beam;
a plurality of mirrors arranged so as to form a ring resonator for confining the laser beam;
means for generating an electron beam to interact with the laser beam so as to produce photons in the form of hard x-rays by Thompson scattering of the laser beam by the electron beam; and
a vacuum chamber forming an interaction chamber where the laser beam and the electron beam interact to product the hard x-rays.

2. The device of further comprising means for interrupting the laser beam so as to form a pulsed laser beam for injection into the ring resonator in a synchronous manner.

3. The device of claim 2 wherein said means for interrupting the laser beam is a plurality of Pockel cells.

4. The device of claim 2 where the means for interrupting the laser beam so as to form a pulsed laser beam for injection into the rig resonator in a synchronous manner further comprises a means for controlling the hard x-ray polarization by controlling the laser beam polarization.

5. The device of further comprising means for amplifying the laser beam to compensate for losses resulting from diffraction of the pulsed laser beam, imperfect reflectivity of the mirrors and scattering of the laser beam by the electron beam.

6. The device of claim 5 wherein said means for amplifying the pulsed laser beam is a recycler that stretches, amplifies and recompresses the pulsed laser beam.

7. The device of, claim 5 wherein said means for amplifying the pulsed laser beam is a low gain amplifier.

8. The device of claim 1 wherein said laser source is a laser operating in a 1–10 TW power range.

9. The device of claim 8 wherein said laser source is a laser utilizing chirped pulse amplification.

10. The device of claim 8 wherein said laser source is a solid state laser.

11. The device of claim 10 wherein said solid state laser is a high power modified Nd:YAG laser.

12. The device of claim 1 wherein said laser source is a laser operating in a 5 kW power range.

13. The device of claim 1 wherein the plurality of mirrors are arranged in a rectangular configuration forming the ring resonator.

14. The device of claim 1 wherein the plurality of mirrors are arranged in a triangular configuration forming the ring resonator.

15. The device of claim 1 wherein at least two mirrors of said plurality of mirrors are off-axis paraboloid concave mirrors focusing the laser beam onto the point within the interaction chamber where the laser beam interacts with the electron beam.

16. The device of claim 15 wherein at least one of said concave mirrors has a window to allow the flow of x-rays outside of the interaction chamber.

17. The device of claim 16, wherein said window is made of beryllium.

18. The device of claim 1 wherein at least one of said mirrors is a high power dielectric mirror.

19. The device of claim 1 wherein said means for generating an electron beam is a radio frequency linear oscillator.

20. The device of claim 1 wherein said means for generating an electron beam is a betatron.

21. A method for generating x-rays, comprising the steps of:
generating subpicosecond laser pulses with a high peak power laser operating in a 1'10 TW power range;
injecting the laser pulses into a ring resonator in a first direction thereby forming a continuous loop;
generating an electron beam in a linear accelerator moving in a second direction opposite to the first direction of the laser pulse; and
focusing the laser pulses upon a point within an interaction chamber where the laser pulses and the electron beam interact by Thomson scattering so as to produce hard x-rays.

22. The method of claim 21 further comprising the step of amplifying the laser pulses moving in the first direction in the ring resonator to replenish the laser energy lost due to diffraction of the laser pulses, imperfect reflectivity within the ring resonator, and scattering due to the interaction of the laser beam with the electron beam.

23. The method of claim 22 further comprising the step of amplifying said laser pulses in the ring resonator to replenish the laser energy lost due to diffraction of the laser pulses, imperfect reflectivity within the ring resonator, and scattering due to the interaction of the laser beam with the electron beam.

24. A method for generating hard x-rays, comprising the steps of:
generating laser pulses having short length and high average circulating power of approximately 5 kW;
injecting the laser pulses into a ring resonator in a first direction thereby forming a continuous loop;
generating in a betatron an electron beam moving in a second direction opposite to the direction of the laser pulses; and
focusing the laser pulses on a point within the betatron so as to intersect the electron beam tangentially thereby causing hard x-rays to be produced via Thomson scattering.

25. A device for generating hard x-rays comprised of:
means for generating a short, tunable laser pulse;
means for confining and recirculating the laser pulse in a predetermined direction;
means for generating an electron beam circulating in a predetermined direction, opposite to the direction of movement of the laser pulse; and

means for generating hard x-rays by Thomson scattering of the laser pulse and the electron beam moving in an opposite direction to the laser pulse.

26. The device of claim 25 wherein the means for generating hard x-rays is comprised of an interaction chamber and a plurality of focusing magnets and optical mirrors.

27. A method for generating hard x-rays comprising the steps of:

generating a laser beam having a high peak power of subpicosecond duration so as to form a pulsed laser beam

directing the pulsed laser beam in a first direction in a continuous loop in a ring resonator;

generating an electron beam in a linear accelerator, said beam being directed in a second direction opposite to the direction of the pulsed laser beam; and

focusing the pulsed laser beam upon a point within an interaction chamber where the laser beam and the electron beam interact at a predetermined intersection angle thereby producing hard x-rays pulses of a predetermined energy level by the Thomson scattering of the laser beam by the electron beam.

28. The method of claim 27 further comprising the step of amplifying the pulsed laser beam in the ring resonator to replenish the laser energy lost by diffraction of the laser pulses, imperfect reflectivity within the ring resonator, and scattering due to the interaction of the laser beam with the electron beam.

29. The method of claim 27 further comprising the step of reducing the pulse length of the generated hard x-rays by varying the intersection angle between the laser beam and the electron beam.

30. A method for generating hard x-rays, comprising the steps of:

generating a laser beam having high average power and short pulse length;

injecting the laser beam in a first direction in a continuous loop in a ring resonator;

generating in a betatron an electron beam moving in a second direction opposite to the direction of the laser beam; and

focusing the laser beam on a point within the betatron thereby causing the laser beam and the electron beam to interact within said betatron so as to produce hard x-ray pulses by Thomson scattering of the laser beam by the electron beam.

31. The method of claim 30 further comprising the step of increasing the energy level of the x-ray pulses by using an electron beam of a predetermined quality to produce self amplified harmonic scattering of the laser pulses thereby generating coherent harmonic hard x-rays.

32. A method for increasing x-ray energy, comprising the steps of:

generating laser pulses with a high peak power laser;

injecting the laser pulses into a ring resonator in a first direction;

generating free electrons composed of electrons within a relativistic electron beam in a linear accelerator, said electrons moving in a second direction opposite to the direction of the laser pulse; and

focusing the laser pulses within an interaction chamber so as to achieve ultrahigh intensity where the laser pulses and the electron beam interact within the interaction chamber via nonlinear Thomson scattering to produce hard x-rays.

33. The method of claim 32 further comprising the step of increasing the energy level of the x-ray pulses by using an electron beam of a predetermined quality to produce self amplified harmonic scattering of the laser pulses thereby generating coherent harmonic hard x-rays.

* * * * *

US005404364A

United States Patent [19]

Kepros

[11] Patent Number: 5,404,364

[45] Date of Patent: Apr. 4, 1995

[54] OPTICALLY PUMPED X-RAY LASER AND APPLICATIONS THEREOF

[76] Inventor: John G. Kepros, 860 S. 600 East, Salt Lake City, Utah 84102

[21] Appl. No.: 175,102

[22] Filed: Dec. 29, 1993

[51] Int. Cl.[6] H01S 3/30

[52] U.S. Cl. 372/5; 372/69; 372/39

[58] Field of Search 372/39, 76, 5, 69

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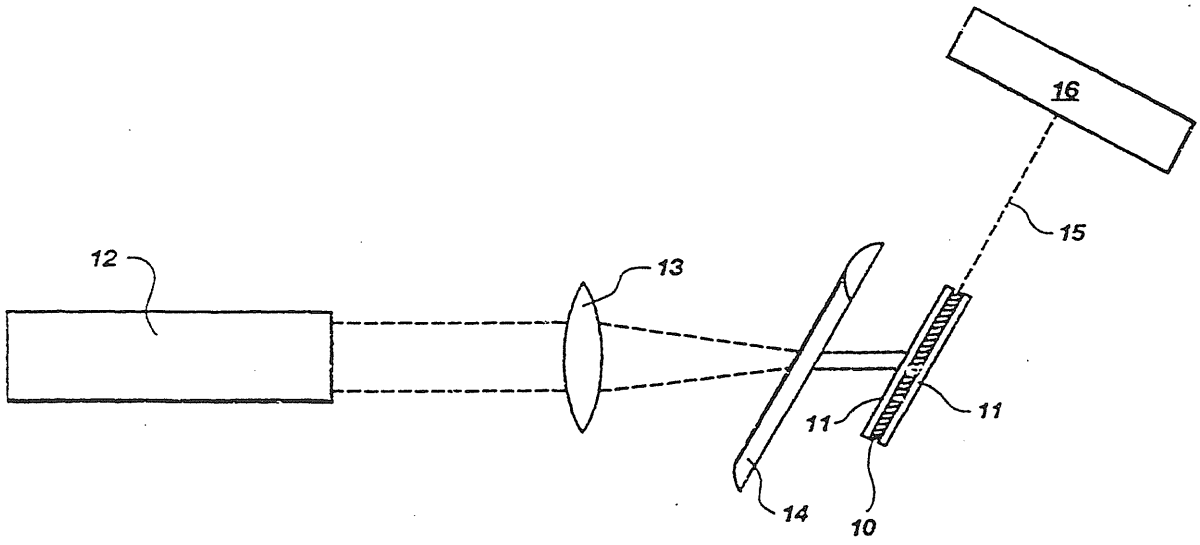
Primary Examiner—Léon Scott, Jr.

Attorney, Agent, or Firm—Trask, Britt & Rossa

[57] ABSTRACT

A method of producing collimated x-radiation by suitably subjecting metallic ions in the presence of lower Z ions to a pulse of laser energy from a conventional laser. An improvement on said conventional laser in order to increase the reliability of production of said collimated x-radiation. An alternative improvement on said conventional laser for similar improvement of said collimated x-radiation. An example of the application of the use of said collimated x-radiation to the art of producing micro-circuitry.

19 Claims, 2 Drawing Sheets



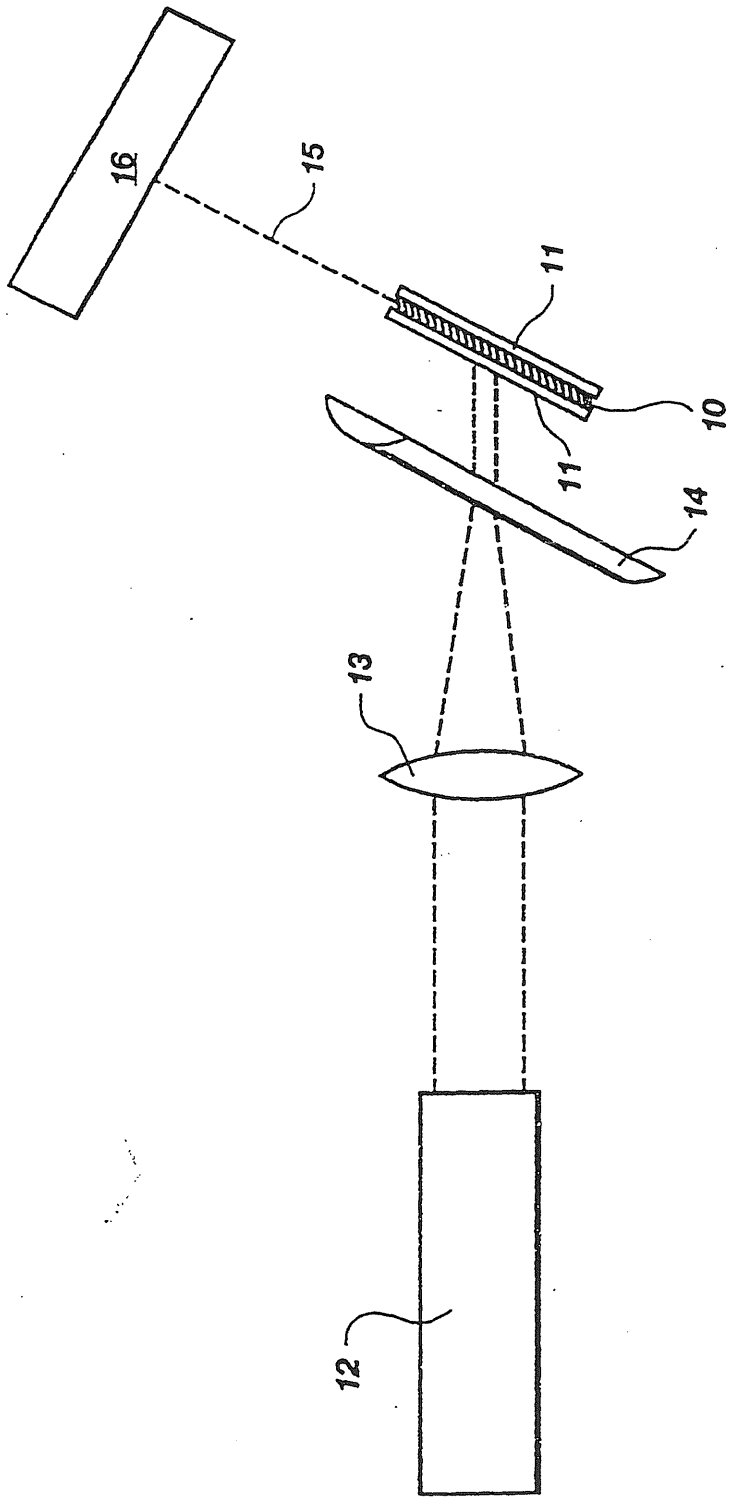


Fig. 1

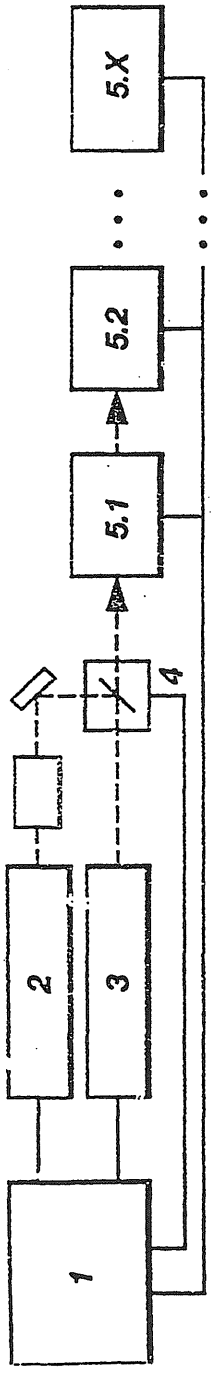


Fig. 2

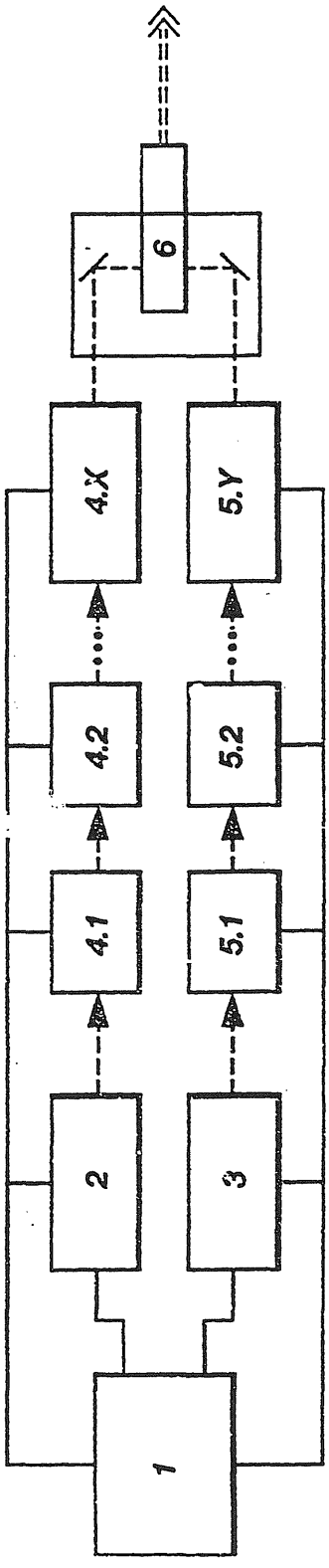


Fig. 3

OPTICALLY PUMPED X-RAY LASER AND APPLICATIONS THEREOF

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to laser-producing collimated x-radiation via impingement of optically-peaked laser radiation onto a metallic ion target.

2. State of the Art

Since the first reported Light Amplification of Stimulated Emission of Radiation (laser action in the visible spectrum) in approximately 1960, continuous progress has been made by various researchers in obtaining laser action at shorter and shorter wavelengths. It has long been felt that an x-ray laser could be developed that would radiate at x-ray wavelengths of less than 5 Angstrom units. X-radiation at these wavelengths is often referred to as a "warm" x-ray and, as such, would travel significant distances through the air.

The potential uses for such "warm" x-radiation having the laser characteristic of being collimated are significant. For example, it may be possible for a physician to foresee the use of a highly collimated x-ray beam as a selective scalpel for use in various types of surgery. Both the chemist and biologist could possibly use x-ray holography as a means for following time dependent three dimensional phenomena at a submicroscopic level. Similarly, the genetic researcher could potentially modify a part of a gene and immediately review said gene to determine if that part had truly been modified. The designer of microcircuitry who presently uses a visible laser to produce a 1.0 centimeter square integrated circuit could theoretically use an x-ray laser to put the sane circuit on a 10.0 micrometer-sized device. Additionally, the interaction of intense coherent x-ray pulses with nuclei could provide valuable new information of interest to physicists.

Potentially, with the use of such "warm" coherent x-radiation, one skilled in the arts of these disciplines could perform such tasks without having to resort to elaborate vacuum systems and thus could operate in ambient air, when appropriate.

One system previously explored for the general purposes of the invention is set forth in U.S. Pat. No. 3,882,312 of Kepros et al. This system, however, achieved only low power sustainable laser beams as only transmitting high peaks of energy under generally unpredictable and uncontrolled conditions.

SUMMARY

In the present invention (as in its progenitor, on which this improvement is based) the feasibility of producing coherent radiation within the x-ray wavelength region has been demonstrated. Further refinements of this basic development will, of course, be forthcoming once the initial concept as taught herein is fully disclosed to those skilled in the art.

It is therefore an object of this invention to provide improvements in lasers capable of producing collimated radiation of the x-ray wavelength.

It is another object of this invention to provide collimated x-radiation having a wavelength of less than 5 Angstrom units.

It is another object of this invention to provide a method for producing collimated x-radiation from metallic ions in the presence of lower Z (lower atomic number) ions by subjecting said metallic ions and lower Z ions to laser radiation of the near infrared spectrum.

It is another object of this invention to provide a method for producing collimated x-radiation from metallic ions in the presence of lower Z ions after subjection to laser radiation of the near infrared spectrum and the essentially complete ionization of both the metallic ions and the nearby lower Z ions with the stripped electrons forming a background cloud. Such a collection of highly ionized multiple species ions with the background electron cloud is commonly called a complex plasma.

It is another object of this invention to provide a method for producing collimated x-radiation from metallic ions in the presence of lower Z ions after the creation of said complex plasma by the formation of quasi-stable molecules consisting of highly-ionized metallic ions and nearby lower Z ions, whereby one or more of the nearby lower Z ions has recombined with an electron changing the nature of the lower Z ion into a lower Z dipole, the result of said recombination is an electrostatic attraction between each highly-ionized metallic ion and a lower Z dipole. (In the specific case where Z=1 (hydrogen), said electrostatic interaction is exceptionally strong.)

It is another object of this invention to provide a method for producing collimated x-radiation after creation of said quasi-stable molecules in this complex plasma by the dipole-allowed transition of an electron from the lower Z component of these molecules to the highly-ionized component of these same molecules.

It is another object of this invention to provide a method for producing collimated x-radiation after the electronic transition in these quasi-stable molecules by the stimulated emission of x-radiation from nearby quasi-stable molecules which have not yet undergone dipole-allowed transition. Said stimulated emission is commonly referred to as lasing.

It is another object of this invention to provide a method of producing pumping laser radiation which simulates so-called "gain-pulse spikes," the purpose of said simulation being to create controllable conditions conducive to said production of x-ray lasing. The method of producing said pumping laser radiation requires the simultaneous use of two laser oscillators, one mode-locked and the other Q-switched, with the appropriate "laser injection" of a pulse (or train of pulses) from the former into the oscillator stage of the latter preparatory to subsequent amplification and final use as a pumping source for said x-ray laser-producing plasma.

It is another object of this invention to provide an alternate method of producing pumping laser radiation which simulates so-called "gain-pulse spikes." The purpose of said simulation is identical to that expressed above. The alternate method of producing said pumping laser radiation also requires the simultaneous use of two laser oscillators, one mode-locked and the other Q-Switched, but with separate amplification of output and final optical merging for simultaneous use as a pumping source for said x-ray laser producing plasma.

It is another object of this invention to provide a method of application of said x-ray laser light in the process of "reading" a hologram produced by a longer wavelength laser. Such "reading" produces an holographic image reduced in dimension by the ratio of said respective wavelengths. The holographic reduction also maintains the topographic characteristics of the original object. These and other objects of this inven-

tion will become more fully apparent by reference to the drawing no. 1 (identical to the drawing of the progenitor patent), drawings 2, and 3 with and accompanying descriptions and the claims relating thereto.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic view of an x-ray-producing laser system.

FIG. 2 is a schematic of a dual-oscillating injection laser system for creating an x-ray lasing plasma.

FIG. 3 is a schematic of a dual oscillator/amplification system for an optical laser system.

DETAILED DESCRIPTION OF INVENTION

FIG. 1 is a schematic of the x-ray laser system and is more fully described hereinafter.

Referring to the drawing, a layer of metallic ions with accompanying lower Z ions is shown generally at 10 and is supported as a thin layer, in this embodiment, by conventional microscope cover glass slips 11 to form thereby a "sandwich". A laser of the near infrared spectrum is shown at 12. Radiation of the near infrared wavelength is shown in outline form by dashed lines emanating from laser 12. A conventional focusing system is shown generally at 13. A cylindrical focusing lens 14 focuses the radiation pulse from laser 12 into a near vertically i.e. at a right angle or acute angle from the vertical and, preferably, at an angle which is normal to said layer of metallic ions and lower Z ions or at an angle 0° to 25° from a direction normal to said layer, linear pulse on the metallic ions and lower Z ions 10. The x-ray laser emission produced from the quasi-molecules is illustrated by dashed lines 15. A detection device for detecting the x-radiation 15 is shown generally at 16.

The quasi-stable molecules capable of producing x-radiation when subjected to laser energy of the near infrared wavelength are molecules containing neutral hydrogen atoms combined with ions of copper, iron or zinc. Compounds of these metals having high solubility in water (the source of hydrogen) were considered in these experiments. In this case, these compounds are copper sulfate, zinc sulfate, and ferrous sulfate. For purposes of simplicity and to assist in the understanding of this invention, the description of the x-ray laser will center around the use of the copper ions as the metallic ions.

In the progenitor patent, a gel was used for ease of handling. In subsequent work, it was found that the gel was irrelevant to the effect. The critical component was the aqueous complexed-solution of $CuSO_4$. In a commonly-used solution (one of several successful concentrations of ions) such as 10E−3M, the relative populations are: Cu, 1; S, 1; 0, 5.55×10E+4; and H, 1.11×10E+5. In such a solution, the copper ion is initially complexed to six hydroxyl radicals. If this general structure were to somehow survive into the plasma state, an allowed Molecular Orbital: Linear Combination of Atomic Orbitals (MO:LCAO) dipole transition is possible. One such transition is:

$$\hat{r}_{ij}=(1S_H|\hat{r}|2P_{Cu+27})$$

The wavelength associated with this transition is 4.75 Angstroms. The unbroadened minimum spontaneous lifetime is estimated as 6.0×10E−11 s. The above transition can be associated with a quasi-stable molecule essentially consisting of a neutral hydrogen atom in the presence of a highly-stripped Cu ion (Cu+27). The hydrogen atom, unlike the hydrogen ion, is strongly attracted to the highly charged copper ion while said hydrogen ion is very strongly repulsed. Also, in the progenitor patent and in fact, in all other patents dealing with x-ray laser action, there is no mention of a molecular transition. There is only a description of atomic action with occasional description of transfer of energy between different components by collisional means. Although said MO:LCAO techniques are known to those skilled in the arts of visible wavelength laser design such as the dye laser, the application of said technology to design of lasers in the x-ray part of the spectrum is heretofore unprecedented.

Several features of the experiments used well-known techniques associated with the arts of laser plasma formation to enhance the efficiency of the experiments. First was the use of microscope cover slips to couple the laser energy into the plasma. Researchers skilled in the related arts associated with Laser-Initiated Fusion have long maintained that the glass microballoon was a key element in said energy transfer. Second, as the plasma was formed in air, the plasma was not freely expanding as it is in a vacuum. This containment gives rise to higher initial plasma temperatures and, potentially, could give rise to higher temperatures throughout the lifetime of the plasma. As the temperature of the plasma is a measure of the kinetic energy stored in the plasma, those skilled in the related art of vacuum plasma formation go to great lengths for even modest magnetic containment of the plasma. Finally, after review of the arts associated with pumping laser operation, the existence of gain-pulse spikes was recognized (and found to exist in the pumping laser). Said gain-pulse spikes are minimized by first "warming up the laser" by blocking lasing in the oscillator stage by physically inserting an opaque object in the cavity for a few initial cycles. After doing so, a so-called nominal pulse is obtained. The nominal pulse is relatively free of intense spikes. On the other hand, if the system is allowed to rest, especially for several weeks, and then operated WITHOUT said "warming up of the laser", the initial pulse has potentially rod-damaging gain-pulse spikes which are subsequently amplified in the amplifier train of the laser. Those skilled in the art of Nd:glass laser operation estimate the intensity of the spikes might be amplified to an intensity two- to three-orders of magnitude above nominal. In such a situation, a 10 GW laser (nominal pulse power) might perform more like a 10 TW laser for its initial pulse. The combined and patient use of said special techniques, in the short term, provide a means for those skilled in the art of x-ray laser development to maximize the efficacy of their laboratory equipment.

In a preferred embodiment, the pumping laser of the instant invention has two coupled oscillator cavities, shown in FIG. 2. The first has a Q-switched Nd:glass system producing a nominal 20-nanosecond pulse at 1.06 micrometers. The second has a mode-locked Nd:YAG oscillator, operating simultaneously at 1.064 micrometers, producing a 30–60 picosecond pulse. This shorter pulse would be injected directly into the Nd:glass oscillator, forming a so-called injection laser oscillator, the output of which would be amplified by means of suitable amplification stages with rods or slabs of Nd:glass or Nd:YLF. Alternatively, said mode-locked pulse could be separately amplified and then combined for final amplification, shown in FIG. 3. In either case, such an inventive pumping system simulates

the condition obtained by operating a ND:glass laser system with gain-pulse spikes present and available to interact with the x-ray source.

As an intense pulse of laser radiation from cylindrical focusing lens 14 (which lens causes the pulse to be essentially focused to a line when viewed in cross section) strikes the aqueous copper sulfate solution 10, especially in the slightly canted configuration, the leading edge of said pulse of radiation causes excitation of the copper ions in said solution system. As the travelling wave front continues to travel along the canted aqueous system (even if only infinitesimally canted) each succeeding part of the pulse front amplifies the previous x-radiation produced from the MO:LCAO molecules in the aqueous system to produce x-radiation travelling along a line defined by the linear pulse front and collinear with the irradiated portion of the aqueous copper surf ate solution system. An angular orientation of the copper sulfate solution system to the axis of the incoming radiation pulse for the presently preferred embodiment has been found to be between nearly zero degrees and approximately 25 degrees.

In the presently preferred embodiment, the pumping source, or laser of the near infrared spectrum which is shown generally at 12, is a Q-switched, vertically polarized, Nd:glass oscillator-amplifier of four stages, at one-time commercially available through the now defunct Apollo Lasers, Inc. This laser operates at a wave length in the near infrared spectrum of 1.06 micrometers and is controlled to produce nominal pulses of duration 20-nanosecond with total energy of up to 200 joules. This translates into an average power of up to 10 Giga-watts. The instantaneous power, in the situation arising in the case of gain-pulse-spikes may be regarded to be as great as 10 Tera-watts. Operation of the system without warns-up produces such power. Alternatively, operation with dual oscillators, as described hereinafter, produces such power.

The x-my source or metallic ion molecule solution sheet was prepared by dilution of a 0.1M aqueous solution of reagent grade, anhydrous copper sulfate ($CuSO_4$) to 10 or 1 millimolar. A sandwich of the solution was then prepared by placing a film of the solution between two microscope cover glasses, sometimes known as cover "slips" (number 1 cover glass, 0.013 cm thick). The thickness of the film was controlled, largely, by the surface tension of the copper sulfate solution. The position of the copper sulfate solution sandwich was arranged to be adjustable within the range of the focal length of the cylindrical lens 14.

Procedures used to detect the x-radiation produced from the metallic ion molecules comprised standard, photographic methods for detecting x-radiation. In one such detector system, double-emulsion, medical x-ray film was used. In this particular system, commercially available film sold under the trade name Kodak NS-392T was used. The film was protected from light by four layers of black photographic paper which had been sealed with photographic tape. The encased film was then wrapped in from one to four layers of 13 micrometer thick aluminum foil to prevent exposure of the film by soft x-rays and by spurious, reflected infrared laser radiation. As the film was exposed (reacted to the effects of x-radiation) only on the first surface or emulsion nearest the radiation source, such exposure is consistent with and supportive of the wavelength (4.75 Angstroms) predicted by the MO:LCAO theory.

In another detection procedure, the photographic film pack, used at 16, was replaced by a slightly modified Polaroid XR-7 x-ray detection camera. The Polaroid XR-7 Camera system is commercially available from the Polaroid Corporation. It is a system with a black mylar window (opaque to visible, ultraviolet, and infrared light), a thin aluminum plate (located approximately 1 cm from the mylar window) is used to press Polaroid Type 54 film against a ZnS intensifier screen. The system, as with many Polaroid Corp. products is "self developing". One modification consisted of taping a single layer of gold leaf to the inside of the black mylar window. The second modification was in protecting the mylar window from blast debris with a sheet of photographic paper or, sometimes, with a layer of aluminum foil. In the configuration with photographic paper shield and gold leaf scattering medium, the camera works as a so-called "powder diffraction" spectrometer. When the camera system is calibrated using normal-angle of incidence copper k-alpha radiation (with wavelength of approximately 1.5 Angstroms), a series of concentric circles, representing the successive diffraction orders is observed. Also, when the angle of incidence is even a few degrees off-normal, the pattern is slightly elliptic. Thus, the appearance of the plasma x-radiation diffraction pattern, in a slightly elliptic pattern only near the third-order position and with the central or zero-order beam also present is consistent with the wavelength, 4.75 Angstroms, predicted by the MO:LCAO model and with a camera system almost ideally aligned normally to the incident x-radiation beam.

The property of collimation of the x-radiation produced, a prime indicator of lasing, was indicated by changing the distance of the detector 16 from the source of radiation. In each instance them was no significant increase in the size of the exposed portion of the film, thus indicating collimation. Cylindrical lens 14 and the glass, metallic ion solution sandwich comprising 11 and 10, respectively, were placed parallel to one another. In this arrangement, the leading edge of the Nd:glass laser pulse pumps the MO:LCAO lasing medium directly in front of material that has just been pumped. Using this travelling-wave method of pumping, a population inversion is created with the result that emitted x-radiation is amplified as it travels along the copper-solution plasma. It should therefore be obvious that media that require high intensity, fast rise-times, and long pumping regions to produce detectable radiation should be easily pumped by this method. On the other hand, the brute-force frontal assault, using other lens systems, results in a very short pumped region that thus limits the gain.

It has therefore been shown that this invention has produced collimation of a beam of radiation and that said radiation was not completely absorbed by intervening air, layers of aluminum foil, and photographic paper, thus indicating that said collimated radiation was warm x-radiation. Furthermore, the absorption characteristics of the radiation with regard to transmission by said materials and subsequent absorption by silver bromide photographic emulsion and also the interaction of said x-radiation with thin gold leaf in a so-called "powder pattern" is consistent with and supportive of the MO:LCAO model used to predict said x-radiation.

The concept of an injection laser is familiar to those skilled in the art of laser design. A lasing system suitably using an injection system is illustrated in FIG. 2. The injection of one laser beam (usually CW or continuous

wave) into the other laser resonant cavity is often used to assure coherence between separate pulses of a pulsed laser. In the present embodiment, the injection aspect is especially useful for producing a nominal laser pulse with intense spikes superposed. This is intended to simulate, in a controlled manner, the conditions associated with transient gain-pulse spikes superposed on a nominal plasma-producing pulse.

The components of such a system have the following functions:

1. The power supply, controls, and timing electronics subsystem energizes the two laser oscillator stages so that they function simultaneously. The power supply charges the capacitor banks which energize both oscillator-stage flash lamps and appropriately energize the flash lamps in the amplifier stages. The system electro-optically controls the output of the mode-locked oscillator so that as few as one pulse is emitted or a train of two or more pulses are produced during the duration of the Q-Switched laser pulse. The subsystem also activates and controls the amplifier isolation devices (used to prevent damage from laser light reflecting from the target or final plasma and returning through the amplifier system).
2. The mode-locked oscillator is used to produce very intense laser pulses of a duration of only a few picoseconds. A common lasing medium for such a device is Nd:YAG. Said mode-locked pulses, operating at 1.064 micrometers wavelength, could be introduced directly into the Q-Switched Nd:Glass oscillator or could be pre-amplified, as required, to obtain the desired system output.
3. The Q-Switched Nd:Glass oscillator, operating at 1.06 micrometers wavelength, blocks all laser function electro-optically until it is ready to fire. At that time, the electro-optic shutter changes its polarization, allowing appropriately polarized light to pass. The combination of the two laser beams is then emitted through the beam splitter to the amplifier-/isolator train.
4. The beamsplitter is a flat partly-transmitting and partly-reflecting passive optical element.
5. The amplifier/isolator train consists of x-number of elements (perhaps up to but not limited to as many as ten, limited by space and cost). The number of amplification stages is dependent on the specific gain characteristics of the amplifying medium, the efficiency of the system design in producing amplification, and the physical limits associated with minimal damage (preferably damage-free) pumping laser operation. The total number of amplification stages is determined by the power-on-target requirements (POTR). In the present embodiment, this is estimated to be approximately 10.0 GW Q-Switched and 1.0 TW mode-locked power.

Commonly, a spatial-filtering, beam-expanding, and return-isolating module is attached to each amplifying stage. Specific designs may not necessarily include complete modules (or even partial modules) with every amplification stage (sometimes considered as an initial cost-savings step). The aforementioned minimum POTR can be achieved by either of the specific designs described herein.

A device, producing pulses similar to the pulses produced by the preceding pumping laser described in FIG. 2, which produces and amplifies the beams in separate channels and finally combines the amplified beams, could also be used to produce intense spikes superposed on a nominal plasma-producing pulse is shown in FIG. 3. This device differs from the previous device by having separate amplifier chains for each wavelength, total simultaneous electronic control of the individual oscillators, and a final stage consisting of a beam-combining optical system.

The components of such a system have the following functions:

1. The power supply, controls, and timing electronics subsystem energizes the two laser oscillator stages so that they operate simultaneously. The power supply charges the capacitor banks which energize both oscillator-stage flash lamps and appropriately energize the flash lamps in the various stages of both amplifier trains. The system electro-optically controls output of the oscillator so that as few as one pulse is emitted or that a train of two or more pulses are produced during the duration of the Q-Switched laser pulse. This system differs from the preceding system by NOT INJECTING the mode-locked pulses into the Q-Switched oscillator laser cavity. The subsystem also activates and controls the amplifier isolation devices (used to prevent damage from laser light reflecting from the target or final plasma and returning through the amplifier system).
2. The mode-locked oscillator is used to produce very intense laser pulses of duration of only a few picoseconds. A common lasing medium for such a device is ND:YAG. Said mode-locked pulses, operating at 1.064 micrometers wavelength could be introduced directly into an appropriate amplifier train to produce a final, short duration pulse (or pulses) with peak power of 1.0 TW delivered from the output element of the beam-combining stage.
3. The Q-Switched Nd:Glass oscillator is used to produce intense laser pulses of duration 20.0–30.0 nanoseconds. Said Q-Switched pulse, operating at 1.06 micrometers wavelength could be introduced into the appropriate amplifier train to produce a final pulse with peak power of 10.0 GW delivered from the output element of the beam-combining stage (POTR).
4. The Mode-lock (M-L) amplifier/isolator train consists of x-number of elements (perhaps up to but not limited to as many as ten, limited by space and cost). The number of amplification stages is dependent on the specific gain characteristics of the amplifying mediums, the efficiency of the system design in producing amplification, and the physical limits associated with minimal damage (preferably damage-free) pumping laser operation. The total number of M-L amplification stages is determined by the POTR. In the present embodiment, for this amplifier train, this is estimated to be approximately 1.0 TW.

Commonly, a spatial-filtering, beam-expanding, and return-isolating module (FEIM) is attached to each amplifying stage. Specific designs may not necessarily include complete modules (or even partial modules) with every amplification stage.

5. The Q-Switched (Q-S) amplifier train consists of y-number of elements (perhaps up to but not limited to as many as ten). The total number of Q-S amplification stages is determined by the POTR. In the present embodiment, for this amplifier train, this is estimated to be approximately 10.0 GW.

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As with the M-L amplifier system, an FEIM is usually associated with each amplification stage. Specific designs may vary with the completeness of each FEIM.

6. The beam-combining optical system takes the two amplified laser beams and co-locates them so that they can be directed to the target which subsequently produces coherent x-radiation.

As indicated hereinabove, the unique laser of this invention may have a multiplicity of uses. A particularly novel use is in the field of microcircuitry design and manufacture.

Specifically, in the case of microcircuitry, the procedure (though novel) is straightforward. First, a hologram is made of a macroscopic integrated circuit (IC), using a visible-wavelength laser such as a He Ne laser operating at 6328 angstroms. Said hologram is then illuminated with a coherent x-ray source such as the one described herein operating at a wavelength of approximately 4.75 angstroms. The illumination of the hologram by such a short-wavelength laser, used in conjunction with a photoresist medium would result in an IC with dimensions magnified by the ratio of the wavelengths. In this specific case, the linear magnification would be 7.51×10E−4 (or 5.63×10E−7 in area magnification). The resultant micro-mask would be identical in function to the original, but occupy less than a millionth of the area. It should be noted that the procedure of holographic magnification using a larger ratio (greater than 1.0) is well known to those skilled in the arts of holography. However, the use of a shorter second wavelength is novel and the use of a laser operating in the x-ray region of the spectrum to "read" the hologram is heretofore unprecedented.

What is claimed is:

1. A method of producing collimated radiation of x-ray wavelength comprising:
- producing a pulse of laser radiation in a near infrared spectrum;
- focusing said pulse of laser radiation into a linear pumping beam; and
- contacting a mixed layer of metallic ions and hydrogen ions with said linear pumping beam at an angle of about 0° from a direction normal to a plane of said layer of metallic ions and hydrogen ions, said pulse of laser energy exciting said metal ions and said hydrogen ions thereby generating a collimated beam of x-radiation.

2. A method of producing collimated radiation of x-ray wavelength as defined in claim 1, wherein said metallic ions comprise copper ions.

3. A method of producing collimated radiation of x-ray wavelength as defined in claim 2, wherein said copper ions and hydrogen ions are present in copper sulfate dissolved in an aqueous system.

4. A method of producing collimated radiation of x-ray wavelength as defined in claim 1, wherein said metallic ions comprise iron ions.

5. A method of producing collimated radiation of the x-ray wavelength as defined in claim 4, wherein said iron ions and hydrogen ions are present in ferrous sulfate dissolved in an aqueous system.

6. A method of producing collimated radiation of x-ray wavelength as defined in claim 1, wherein said metallic ions comprise zinc ions.

7. A method of producing collimated radiation of x-ray wavelength as defined in claim 6, wherein zinc ions and hydrogen ions are present as zinc sulfate dissolved in an aqueous system.

8. A method of producing collimated radiation of x-ray wavelength as defined in claim 1, wherein a neodymium-doped laser operable to emit laser radiation at a wavelength of about 1.06 micrometers is utilized to produce said pulse of near infrared radiation.

9. A method of producing collimated radiation of x-ray wavelength as defined in claim 8, wherein said pulse of radiation has a pulse front which rises exponentially.

10. A method of producing collimated radiation of x-ray wavelength comprising:
- producing a pulse beam of collimated laser radiation in a near infrared spectrum;
- placing a mixed layer of metallic ions and hydrogen ions in the path of said beam, the plane of said layer forming an acute angle, up to and including a right-angle, with said beam; and
- emitting a collimated beam of x-ray radiation directly from said layer upon striking said layer with said pulse beam.

11. Apparatus for producing a high power x-ray laser beam:
- a laser system producing a pulse of laser radiation in a near infrared spectrum, said laser having two oscillation cavities, one cavity feeding the other;
- a focusing system capable of focusing said pulse of laser radiation into a linear beam;
- a mixed layer of metallic ions and hydrogen ions in the focal range of said focusing system with a plane of said layer being transverse to a plane of said beam; and
- means to pump said laser system to cause a pulse of laser energy in a near infrared spectrum to excite the metal ions and the hydrogen ions to generate a beam of collimated x-radiation.

12. The apparatus of claim 11, wherein said laser system comprises a first laser producing a nominal 20 nanosecond pulse at 1.06 micrometers and a second laser capable of operating simultaneously with said first laser, said second laser producing a nominal 30–60 picosecond pulse (or pulse train) at 1.064 micrometers, said second pulse (or pulse train) injecting directly into the oscillator of said first laser.

13. The apparatus of claim 11, wherein said pulse of said laser system is directed into an amplifier system.

14. The apparatus of claim 13, wherein said amplifier system contains Nd:Glass or Nd:YLF amplification members through which said laser output pulse is passed.

15. Apparatus for producing a high power x-ray laser beam:
- a laser system producing a pulse of laser radiation in near infrared spectrum, said laser having two oscillation cavities operating simultaneously;
- a focusing system capable of focusing said laser radiation into a linear beam;
- a mixed layer of metallic ions and hydrogen ions in the focal range of said focusing system with a plane of said mixed layer being at an acute angle up to a right angle to a plane of said beam; and
- means to pump said laser system to cause a pulse of laser energy in a near infrared spectrum to excite said metal ions and the hydrogen ions to generate a beam of collimated x-ray radiation.

16. The apparatus of claim 15, wherein said laser system comprises a first laser producing a nominal 20.0 nanosecond pulse at 1.06 micrometers and a second laser capable of operating simultaneously with said first

laser, said second laser producing a nominal 30.0–60.0 picosecond pulse (or pulse train) at 1.064 micrometers.

17. The apparatus of claim 15, wherein said pulse of said laser system directed into parallel amplifying systems.

18. The apparatus of claim 17 wherein said amplifier system contains Nd:Glass, ND:YLF, or Nd:YAG amplification members through which said laser output pulse is passed.

19. The apparatus of claim 17 wherein the outputs of the two parallel amplification systems are combined into a single pulse by an additional optical system.

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US005467362A

United States Patent [19]

Murray

[11] Patent Number: 5,467,362

[45] Date of Patent: Nov. 14, 1995

[54] PULSED GAS DISCHARGE XRAY LASER

[76] Inventor: Gordon A. Murray, 20306 Melville St., Orlando, Fla. 32833

[21] Appl. No.: 285,292

[22] Filed: Aug. 3, 1994

[51] Int. Cl.[6] H01S 3/30

[52] U.S. Cl. 372/5; 372/62; 372/65

[58] Field of Search 372/61, 62, 65, 372/5

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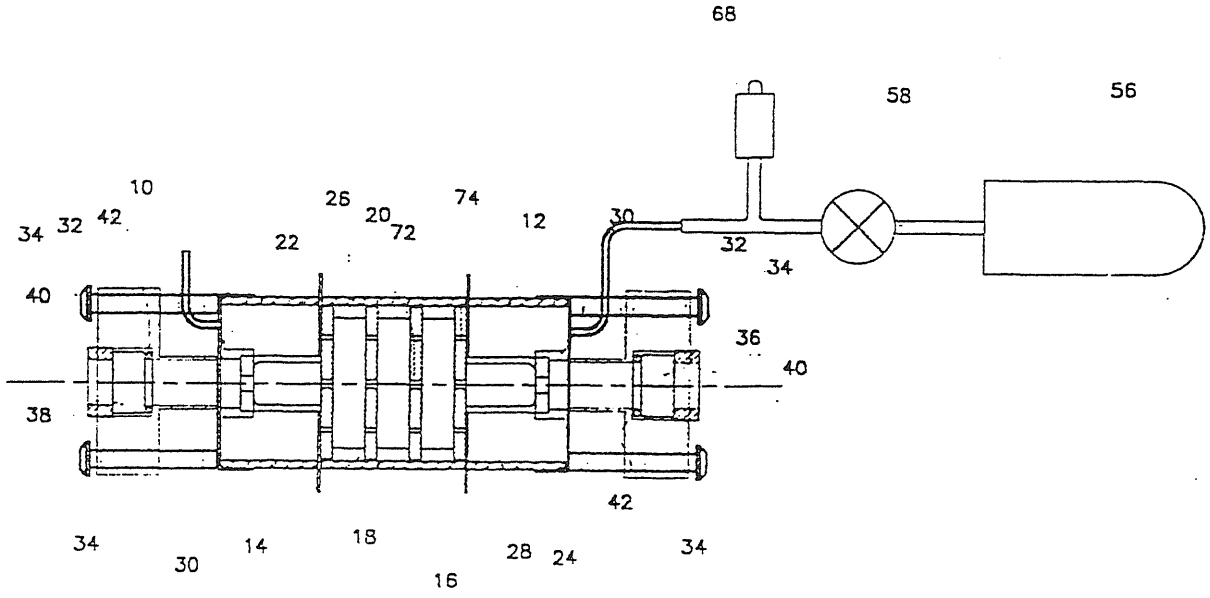
Primary Examiner—Léon Scott, Jr.

[57] ABSTRACT

A high current, pulsed, high repetition rate, electric discharge, extreme ultraviolet and Xray laser. The low inductance discharge bore is constructed from a plurality of discs (18). The bore segments are separated from one another by spacers constructed from a refractory electrical insulator (20). The components in contact with the gas discharge are constructed from high temperature materials with low sputtering rates and low rates of ion burial. Gas return holes (74) are provided in the bore segments discs. Xray reflecting mirrors form an optical cavity.

21 Claims, 5 Drawing Sheets



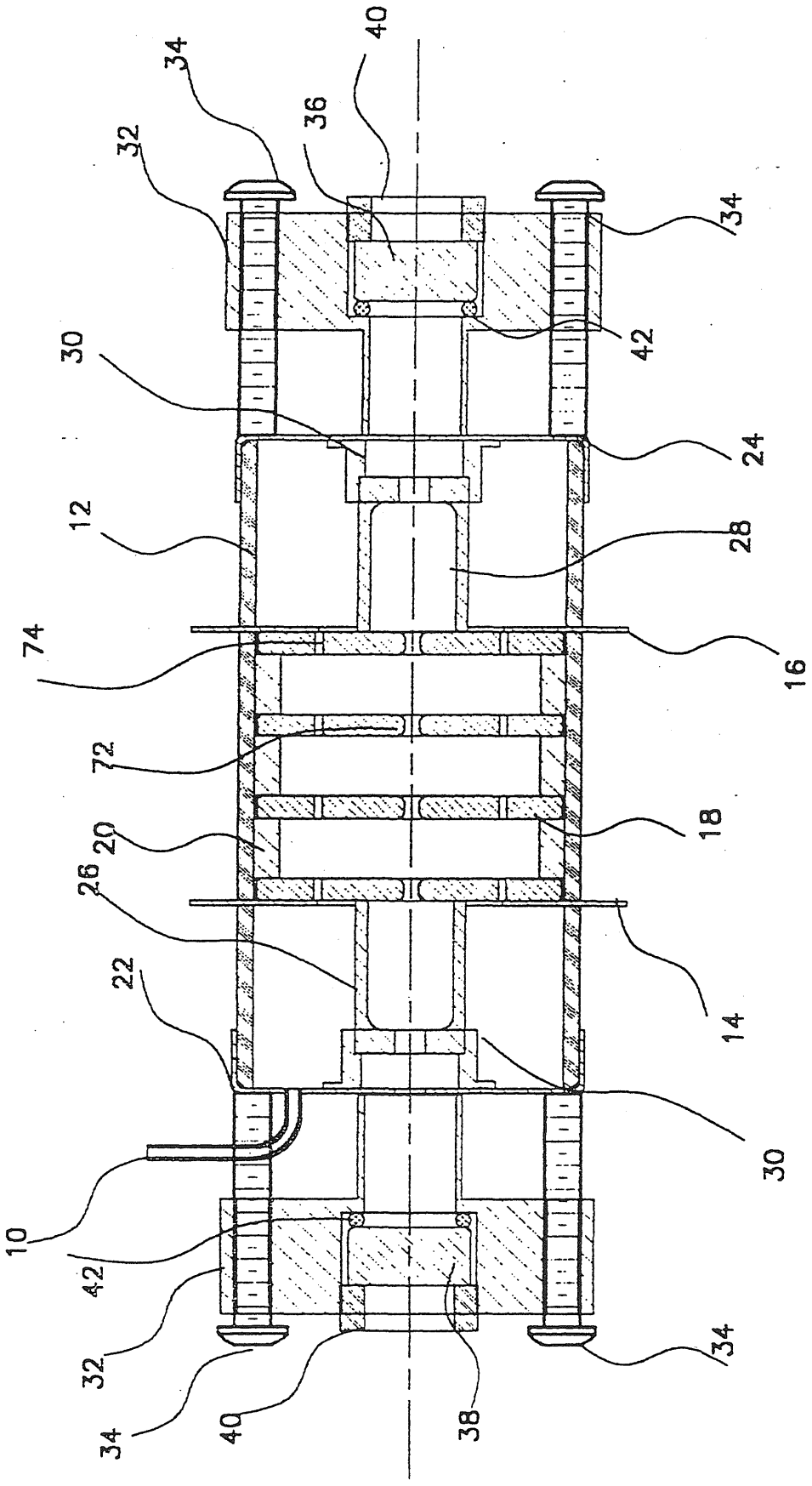

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FIGURE 1

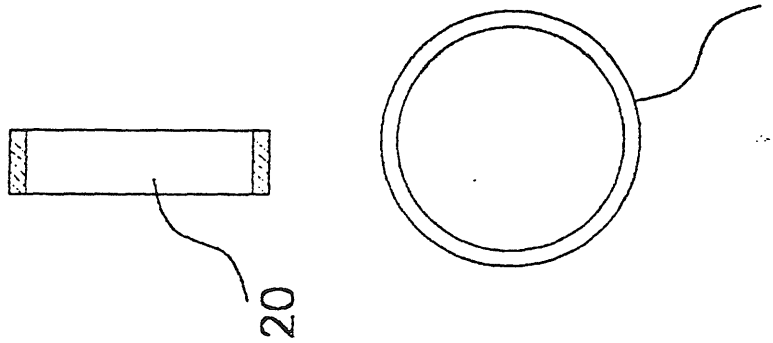

FIGURE 3

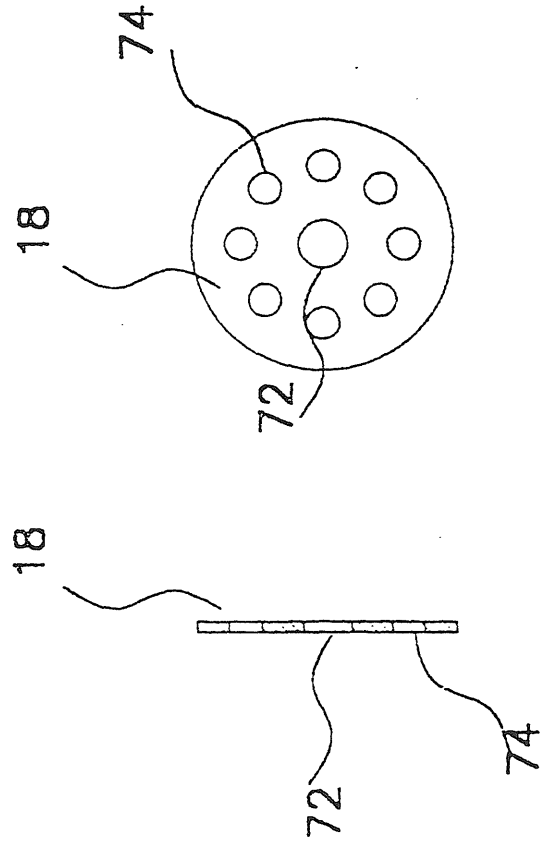

FIGURE 2

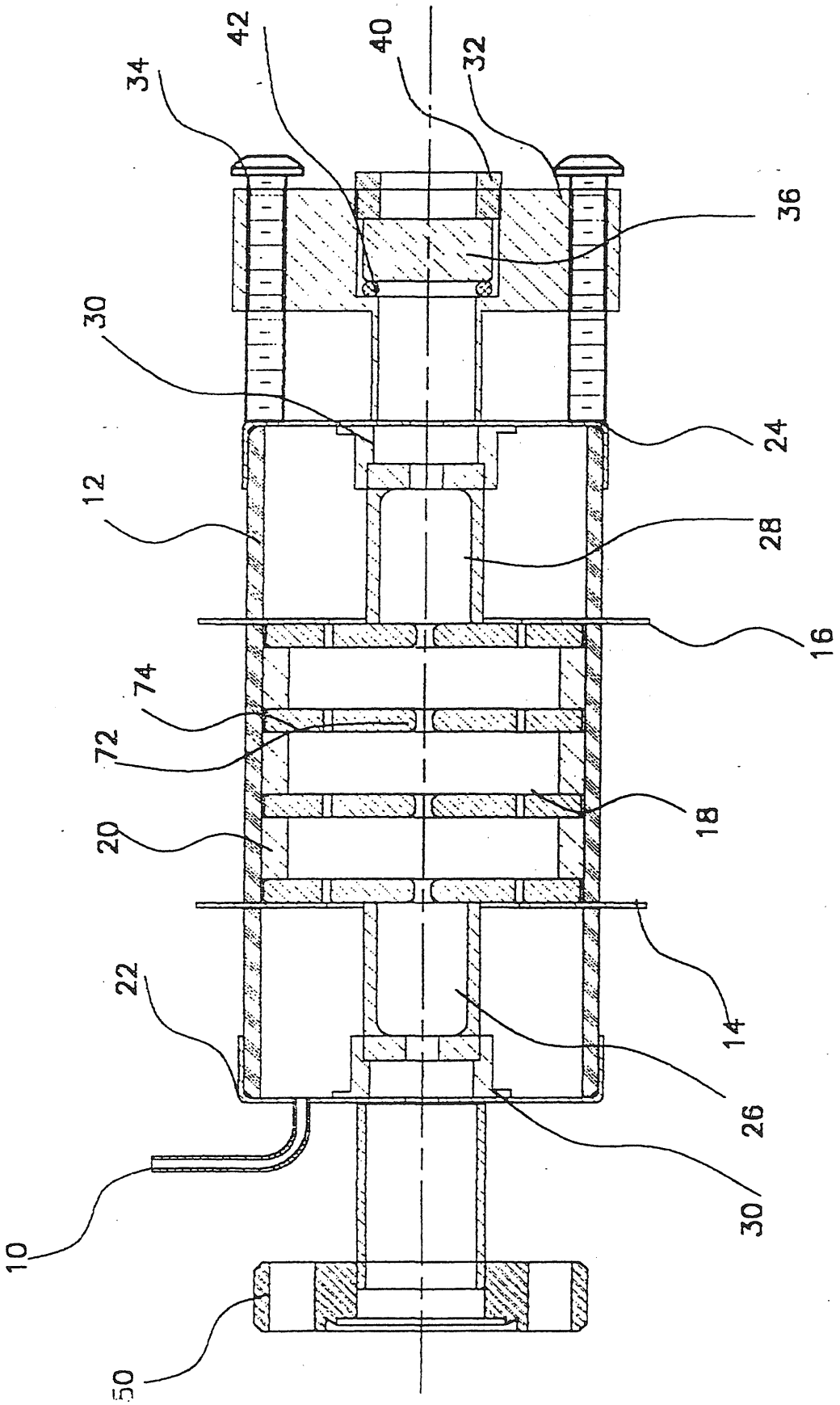

FIGURE 4

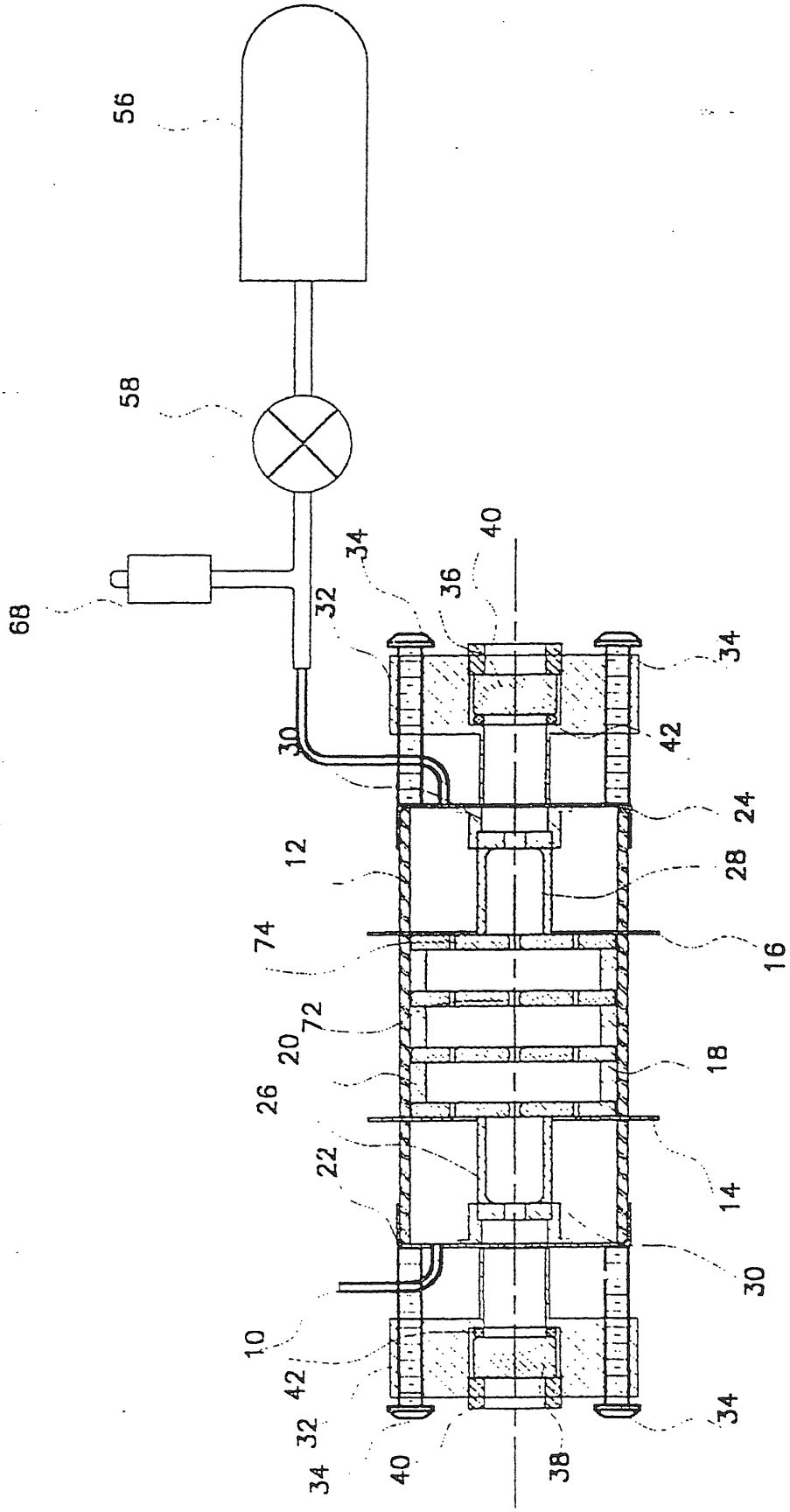
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FIGURE 5

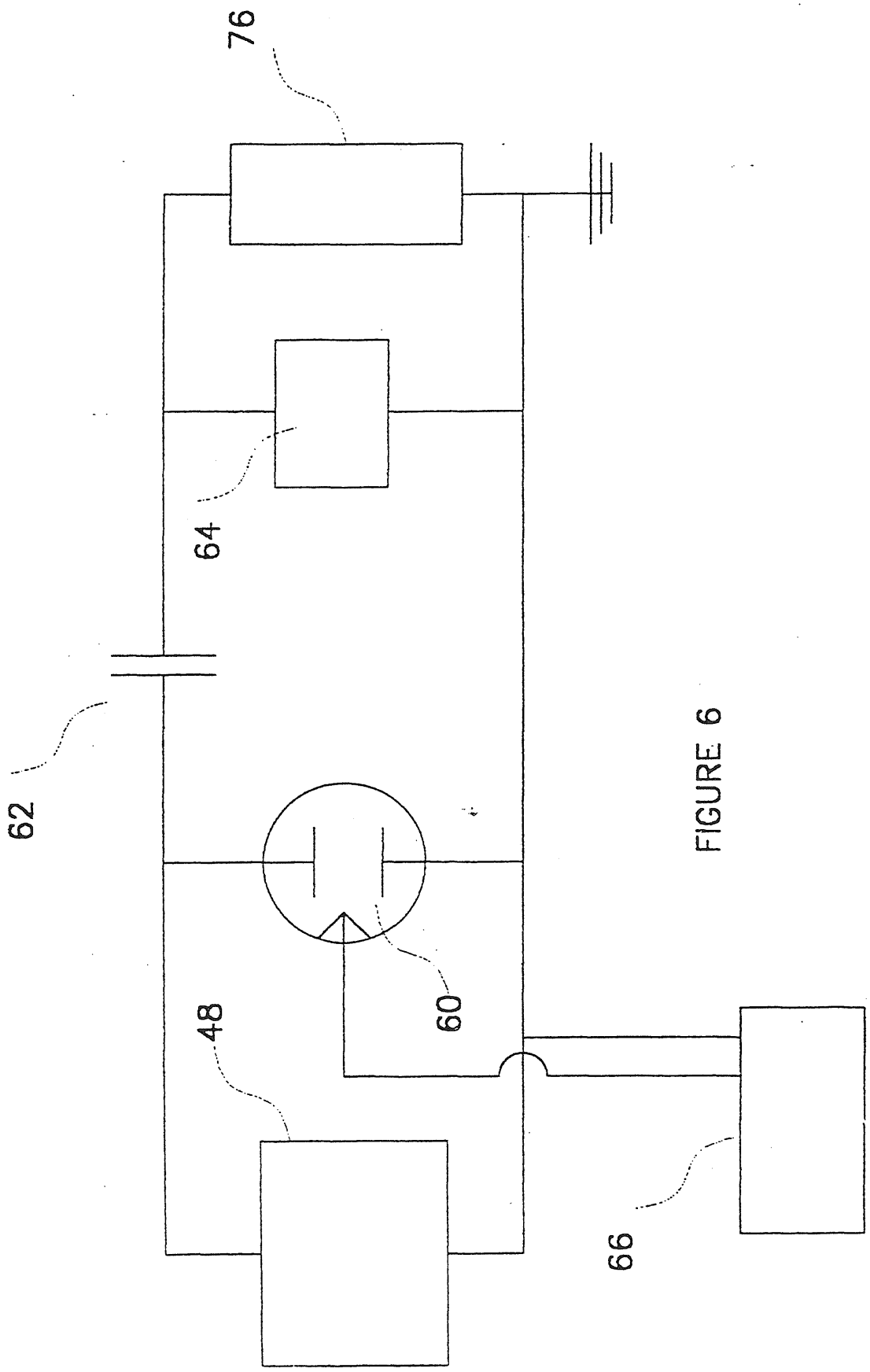

FIGURE 6

PULSED GAS DISCHARGE XRAY LASER

BACKGROUND

1. Field of Invention

This invention relates to short wavelength gas discharge lasers. In particular to pulsed extreme ultraviolet and Xray lasers.

2. Description of Prior Art

Pulsed Xray and extreme ultraviolet lasers operate on transitions between highly ionized atomic states. For example in Argon the fourth to fifteenth ionized states of the atom produces excited states that generate transitions in the soft Xray and extreme ultraviolet region of the electromagnetic spectrum. Many extreme ultraviolet lines with wavelengths below 200 nm have been observed, several have produced pulsed laser output. The conditions to produce Xray and extreme ultraviolet laser output are created during a pulsed gas discharge or in it's afterglow. Pulses with peak current densities of thousands of amps per square centimeter are required to generate large numbers of such highly excited states. To produce high peak currents a very low inductance electrical pulser configuration is required. Additionally the discharge is confined to narrow diameter cylindrical region by the laser geometry. The narrow bore produces a high current density. High peak current discharges are generated by the rapid switching of a capacitor. The capacitor is charged to a high voltage, typically 10–30 kilovolts. The energy stored in the capacitor is switched into the discharge by a fast high voltage switch such as a thyratron.

Heretofore described pulsed discharge Xray and extreme ultraviolet lasers have used continuous bore tubes. In these lasers a gas discharge is produced in a narrow bore tube. The tube may be filled with a low pressure gas. In some cases the inner wall material of the tube is evaporated during the electrical pulse to produce the active plasma of the discharge. A major disadvantage of this method is that the tube material is rapidly consumed by the discharge due to sputtering and evaporation even when the tube is filled with low pressure gas. Xray lasers have used narrow diameter continuous bores described as capillaries. The discharge is known as a capillary discharge. Similarly gas discharge extreme ultraviolet lasers have used larger diameter continuous bores constructed from fused silica.

The production of Xray laser output from a pulsed discharge requires high peak current densities in excess of 5000 amps per square cm. High current gas discharges like this are known to cause ion and electron sputtering and ion burial at surfaces near the gas discharge. Sputtering and ion burial results in gas loss from the laser system. The magnitude of the gas loss depends upon the discharge bore geometry, the discharge current and the construction material of the internal laser components. Fused silica has a relatively high sputtering and ion burial rate. Gas is lost rapidly in lasers constructed with fused silica bores and material from the bore contaminates the active laser gas. The contamination may absorb at the laser wavelength and reduce or extinguish laser output.

Additionally in these devices the pulsed electrical discharge produces a gas pumping effect in which the gas is pumped from one end of the tube to the other. The magnitude and direction of this pumping are dependent upon the discharge current and the pulse repetition rate and other factors. The gas pumping effect results in a reduction of laser output energy in sealed off systems. Often gas return lines

are added to the laser to allow for pressure equalization. Also, the laser may be operated non sealed off with a flowing gas source. A further problem caused by gas pumping is the differential pumping rates of different gases, this leads to gas separation in discharges consisting of binary or ternary gas mixtures.

The pulse repetition rate in continuous bore lasers is limited due to bore heating. The pulsed gas discharge causes heating which can melt or soften the bore at high repetition rates. This has limited the repetition rate of continuous bore lasers.

There is no sealed off long life laser source of extreme ultraviolet or Xrays.

SUMMARY OF INVENTION

An object of the present invention is to provide a long life source of high average power, high peak power, Xray and extreme ultraviolet laser output below 200 nanometers. The laser might be used to expose photoresists to produce integrated circuits. A further object is to provide a laser that can operate at high repetition rate and is capable of operating at the high temperatures produced by the high power loading caused by high repetition rate operation.

A further advantage is that the new laser can produce greater Xray and extreme ultraviolet laser output than continuous bore laser. The high current densities that are required to generate Xray lasing are produced by creating a high current density gas discharge in a small diameter segmented bore laser. Myers U.S Pat. No. 3,501,714 has described a segmented bore laser for low D.C. currents. Improvements on this design, Hobart U.S. Pat. No. 4,378,600, have increased heat conduction to the cooled ceramic wall and improved gas return, Carlson U.S. Pat. No. 4,719,638.

The pulsed high current discharge causes high sputtering and subsequent bore damage. A segmented bore discharge tube can withstand much larger current densities than a continuous capillary discharge bore, because it is constructed from materials with lower sputtering rates. The Xray and extreme ultraviolet laser output increase non linearly with the increase in current. Above the laser threshold the laser output increases much more rapidly than linearly with current increase. A segmented bore Xray laser can produce much higher Xray output because higher current densities can be produced before bore damage occurs.

Additionally the refractory metal discs that constitute the in bore segments enable the laser to withstand the high temperatures produced by high power dissipation. The high power dissipation is a consequence of operating the laser at high repetition rate. The high repetition rate is required to maximize the average power output of the laser. The average power is the product of single pulse energy and repetition rate. Heretofore pulsed discharge Xray lasers with continuous bores were limited to repetition rates of a few pulses per second. This is due to the lower melting points and the higher sputtering and ion burial rates of the continuous bore materials. A segmented refractory metal bore can operate to higher repetition rates.

The bore is segmented because the discs are made from a refractory metal that is electrically conducting. The bore segments are separated by spacers fabricated from an electrical insulator such as fused silica or ceramic. The segment spacers are located at the edges of the discs and are not in contact with the gas discharge. Therefore the spacers do not reach the high temperatures generated on the discharge axis.

Also the spacers are not exposed to significant sputtering or ion burial. The refractory metal bore segments are very resistant to sputtering and ion burial. These processes remove gas from the discharge and damage the bore. For example Tungsten has a sputtering rate approximately a factor of 100 lower than fused silica. This is especially important at the high peak current densities used to generate Xray laser output.

A further advantage of the laser is the vaporized and ionized bore materials do not absorb at the laser wavelengths. In high peak current pulse discharges some of the bore and electrode materials are vaporized and ionized. The materials forms an ionized metal vapor plasma. This plasma can absorb strongly at the laser wavelength particularly in the Xray region. Refractory metals have a high atomic number which do not absorb significantly in the Xray spectral region in which the laser operates. Also refractory metals have higher melting points and produce lower density metal vapor plasmas than lower melting point metals such as Aluminum. This results in less plasma contamination from metal vapor. Contamination can cool the plasma and reduce the degree of ionization in the plasma. Cooling here refers to reducing the average electron energy in the plasma. A high average electron energy is advantageous. Plasma cooling occurs in capillary discharges near the capillary wall. Since the invention does not have a continuous wall surrounding the gas discharge there is less plasma cooling. This is an advantage of the laser geometry.

A further advantage of the laser is that it is constructed entirely from materials and seals capable of withstanding a high temperature bakeout. A high temperature bakeout is typically required to obtain a long sealed off operating life. Sealed off operation eliminates the need for support equipment such as a vacuum pump and a source of active laser gas. The equipment required to control gas flow and pressure adds significantly to the bulk and weight of the laser system. The high temperature materials are also essential for high repetition rate operation. The high repetition rate may dissipate kilowatts of heat. This can result in the temperature on the laser bore reaching up to 2500 centigrade. Previous lasers. Marling and Massey et at, Steden have been constructed from materials that could not withstand operating temperatures above approximately one hundred and fifty centigrade. Additionally previous lasers could not be baked out above approximately one hundred and fifty degrees centigrade.

Sealed off operation eliminates the need for support equipment such as a vacuum pump and a source of active laser gas. The equipment required to control gas flow and pressure adds significantly to the bulk and weight of the laser system.

An object of the electrical pulsing system is to produce a fast pulse. The fast pulse lead to high peak currents that are required to produce the highly ionized states that generate the deep ultraviolet lasing. The generation of a fast pulse requires that stored electrical energy be rapidly transferred to the gas discharge. An object of the laser tube design is to minimize the electrical inductance of the tube.

A gas refill system may be attached to the laser to compensate for any gas consumption caused by discharge processes.

Further objects and advantages of my invention will become apparent from a consideration of the drawings and ensuing description of it.

DESCRIPTION OF FIGURES

In the drawings, like or corresponding parts are designated with the same reference numerals.

FIG. 1 shows a sectional view of the segmented bore pulsed Xray laser discharge tube, with a front and rear mirror.

FIG. 2 shows a bore segment.

FIG. 3 shows a bore segment spacer.

FIG. 4 shows a sectional view of the segmented bore pulsed Xray laser discharge tube, with a rear mirror only, the output end couples directly into vacuum by way of a vacuum flange.

FIG. 5 shows a pulsed laser system including the pulse a gas pressure control system for long term sealed off operation.

FIG. 6 shows the electrical circuit to produce high peak current pulses in the laser.

DESCRIPTION OF INVENTION

FIG. 1 shows the segmented bore pulsed Xray laser in a sectional view. The tube 12 made be fabricated a ceramic or fused silica. Fused silica TRUE BORE may be used or alumina ceramic with internal diameter tolerances of +/–0.25 mm or better are available from WESGO DURAMIC. If a tighter tolerance is required the internal surface of the ceramic may be machined. The tube has a wall thickness of 2 to 4 mm. The bore segments 18 are discs typically constructed from Tungsten or other refractory metal. FIG. 2 shows a bore segment. The Tungsten discs are typically 10 millimeters to 50 millimeters in diameter but may be smaller or larger and typically a millimeter to a few millimeters thick. The entire disc may be machined or punched from a sheet of refractory metal such as Tungsten or Molybdenum, but other materials may be used. Tungsten and Molybdenum sheet may be obtained from TELEDYNE ADVANCED MATERIALS. As can be seen in FIG. 2 the disc has a central aperture 72. This is the discharge aperture. This aperture is typically 0.25 millimeters to 2 millimeters diameter. The apertures situated off the central axis 74 are gas return holes. The gas return apertures each have a diameter less than that of the central discharge aperture. The bore segment spacer 20 shown in FIG. 3 is slightly smaller diameter than the internal diameter of the tubular vacuum vessel 12. As shown in FIG. 1 a bore segment spacer is located between adjacent disc bore segments. The spacers separate the discs by approximately 2 mm, but this distance may be larger or smaller. FIG. 1 shows a laser consisting of four bore segments and four spacers however lasers may consist of more or less bore segments and spacers. Typically an extreme ultraviolet laser with longer wavelength would use more discs and spacers than a short wavelength Xray laser. An extreme ultraviolet laser might use tens of discs. FIG. 1 shows the anode and cathode electrical connections adjacent to the first and last bore segments. The anode and cathode connections 14, 16 penetrate the body of the tubular vacuum vessel 12. The purpose of these connections is to minimize the electrical inductance of the discharge tube. A low inductance results in a more rapid current pulse and hence higher peak currents. A hollow cathode 26 is located at one end of the discharge tube, a hollow anode 28 at the other end. 26 and 28 are made from a refractory metal such as Molybdenum or Tungsten. These materials are available from TELEDYNE ADVANCED MATERIALS. 26 and 28 are attached to 22 and 24 respectively by mounting components 30. The entire assembly is contained within a tubular vacuum vessel 12. At each end of the laser tube an adjustable mirror mount 32 is welded to the end caps 22 and 24. The mirror mounts may be adjusted by the adjustment

screws 34. Appropriately coated optical components to produce laser action are located coaxial with the discharge bore in each mirror mount 36 and 38. The rear mirror 36 is typically coated to maximize the reflectivity at the lasing wavelength. The front mirror 38 is coated with a reflective coating to maximize the laser output power. The substrate of the front mirror 38 also transmits at the laser wavelength. The minors are sealed to the laser body by sealing rings 42. Pressure to cause compression and sealing of the sealing rings is applied by the compression rings 40.

FIG. 4 show a laser tube with a vacuum flange 50. attached to one end of the laser. The flange is in place of an output mirror. The laser gain is high enough to allow lasing with one mirror or without mirrors.

FIG. 5 shows the laser system with a gas reservoir and valve. 56 is a gas reservoir, 58 is a valve separating the reservoir and the laser tube. A pressure sensor 68 is attached to the laser tube.

FIG. 6 shows a diagram of an electrical pulser used to electrically excite the laser. The pulse power system comprises a high voltage power supply 48. a capacitor 62. a pulse forming network 64. a high voltage switch 60 and a trigger mechanism 66 for the high voltage switch. 76 is an electrical symbol for the laser.

DESCRIPTION OF PREFERRED EMBODIMENT

The preferred embodiment shown in FIG. 1 exhibits general cylindrical symmetry. The preferred embodiment is optimized for Xray laser output. an extreme ultraviolet version of the laser would be longer. The segmented Tungsten disc bore is contained within a tubular vacuum vessel 12. The Tungsten discs are separated by insulating spacers made from fused silica. The fused silica spacers and the discs have outer diameters somewhat smaller than the internal diameter of the tube. The spacers are approximately 2 mm thick in the radial dimension. The discs are spaced from one another by approximately 2 mm and are approximately 12 mm diameter. The tube is typically fabricated from a ceramic material such as Alumina. The anode and cathode electrode connections 14. 16 are joined to the tube and penetrate the outer wall of the tube for the purpose of connecting electrically to the electrical pulser. The distance between the anode and cathode connections is approximately 20 mm The tube extends beyond the electrode penetrations and terminates in end caps 22. 24 at each end which are joined to the tube. The internal tube section between the electrode penetrations and the end caps is made up of cylindrical electrode sections 26. 28 of external diameter approximately half that of the ceramic tube. The internal diameter is greater than the bore diameter. These regions function as a hollow cathode and hollow anode electrode. 26 and 28 slip fit into mounting components 30. These components allow for axial expansion and contraction of the laser bore and electrode assembly due to temperature changes. The components 30 are joined to the end caps 22 and 24. The end caps are joined to mirror mounts at each end. The mirror mounts hold mirrors 36 and 38 which provide appropriate reflectivity at the lasing wavelength. The mirrors may be multilayer metal coated to give high reflectivity in the soft Xray region. The mirrors are be sealed to the mirror mounts by a compression seal 42. The mirrors are pressed against the seal by a compression ring 40. The overall length of the laser is approximately 120 mm. The entire assembly is filled with low pressure gas and is gas tight. A gas fill port 10 permits the laser to be evacuated and filled with low pressure active gas. The laser may be sealed off by pinching off or valving off the gas port.

In FIG. 6, the main storage capacitor 62 is charged to a voltage produced by the high voltage power supply 48. This voltage is typically between 10,000 volts and 40,000 volts although it may be higher or lower. A gas electric switch 60 such as a thyratron or spark gap is used to rapidly switch energy stored in the capacitor into the gas. The thyratron switch 60 is triggered into conduction by the trigger unit 66. This action produces a high voltage pulse at the cathode connection 14 in FIG. 1. A high potential difference is produced between the cathode and the anode. This causes gas breakdown and the formation of a gas discharge between the cathode and the anode through the central apertures. The discharge persists for the time of the applied current pulse. The discharge circuit and the laser tube are constructed to give a low electrical inductance. The low electrical inductance produces a rapid current pulse. The discharge is constrained to the central aperture in the Tungsten discs 72 since this aperture has the largest cross sectional area. A high current density gas discharge is created. The high current density produces a highly ionized plasma with low contamination levels. This type of plasma generates large numbers of highly ionized atoms. Population inversions are created between the highly ionized levels either in the gas discharge or by recombination in the afterglow. The afterglow occurs mainly after the current pulse has ceased and the plasma is cooling. Laser action in the extreme ultraviolet and Xray region results from stimulated emission from the population inversions generated by the discharge.

The high current gas discharge produces a population inversion between excited ionized states. Radiative transitions between these states produce extreme ultraviolet and Xray radiation. Examples are the 17.2 nanometer line of the Krypton spectrum or the 46.9 nanometer Argon line. Very high optical gain is produced by the population inversion. This results is laser output being produced. The laser output can be super fluorescent in which case no mirrors are required. Alternatively laser mirrors aligned with the discharge axis can form a laser resonator to extract the laser output. Appropriately coated laser mirrors are placed coaxial at the ends of the laser tube 36 and 38. The mirrors terminate the gas confining vessel and are in direct contact with the gas fill. Xray laser output is produced at the output laser mirror. Alternatively ultraviolet transmitting windows mounted at may be used to terminate the gas confining vessel. The current pulsing is repeated at regular intervals. Rapid repetition of the pulsing up to 5000 times per second results in considerable heating of the bore segments. In which case the tube 12 may be liquid cooled. The bore temperature may rise to approximately 2500 centigrade. Materials with low melting points are unsuitable for the construction of the bore.

During the high current discharge pulse a pumping action is produced which pushes the active gas is from one end of the tube to another. The effect is known in the art as gas pumping. The direction depends upon a number of factors including bore diameter and discharge current. The gas pumping results in a pressure differential along the tube. The gas flows back to equalize the pressure through the gas return apertures 74 in the Tungsten bore segments 18.

An alternative configuration is shown in FIG. 4. One end of the laser is terminated by a laser mirror. The other end is terminated with a vacuum flange 50. The laser is not sealed off and may be connected to a vacuum system. A source of low pressure gas is used to maintain the correct gas pressure in the laser discharge region. Typically the laser output does not transmit well through air. This arrangement allows the

laser radiation to directly couple into a vacuum chamber where the beam propagates without significant attenuation. The flange may also couple the laser into a low pressure gas chamber that is filled with low pressure gas. The low pressure gas is chosen such that it is transmitting at the wavelength of the laser radiation. Other similar arrangements in which the laser uses two mirrors or one mirror and a window or no mirrors are possible. In these cases the vacuum flange is attached to the vicinity of the output mirror or output window.

FIG. 5 shows a laser system including a gas reservoir to compensate for consumption of the active gas by plasma processes. The gas reservoir 58 contains the active gas or active gas mixture at a pressure greater than the laser tube pressure. The reservoir is connected to the laser tube through a valve 56. A measured volume of gas may be added to the laser tube by opening and closing the valve. Other arrangements with more than one valve are possible. Gas pressure in the laser tube may be reduced by consumption of the active gas by sputtering or ion burial. The gas reservoir is used to maintain the pressure of the active gas in the laser at close to the optimum pressure for lasing. A pressure sensor 68 may be added to the laser tube. An electronic feedback controller or a microprocessor system, not shown, may be used to control a solenoid valve to automatically maintain the gas pressure near the optimum for lasing.

The discharge apertures in the bore segments at the anode and cathode end may be modified. The diameter of the discharge apertures are increased as the bore segments near the anode or cathode. Typically the first few segments at each end would be modified. The first segment at each end would be approximately 3 times the main bore diameter. The aperture diameter in subsequent segments would decrease in diameter until the diameter of the bore was reached.

The laser may produce single tranverse mode, TEM00 output or multimode output. The laser mode depends upon the diameter of the central axial bore apertures, the mirror separation and the radii of curvatures of the mirrors. Typically the mode can be best controlled by the bore diameter.

The tube may be placed within a solenoid magnetic field. The magnetic field can increase the ionization density in the discharge plasma.

The laser tube may be surrounded by a liquid cooling jacket to remove excess heat. The cooling jacket is situated on the outside diameter of the laser tube.

An alterative optical arrangement in which the laser tube is terminated with ultraviolet transmitting windows is also possible. An example of suitable materials for extreme ultraviolet widows would be Magnesium Fluoride or Lithium Fluoride.

Only the section of the bore segment in contact with the gas discharge need be fabricated from a low sputtering and low ion burial rate material. The outer region of a bore segment may be fabricated from many materials and joined to the refractory material.

Conclusions, Ramifications and Scope of Invention

The invention provides a much improved pulsed extreme ultraviolet and Xray laser. The laser can operate at high repetition rate and sealed off. The laser can be used a source of intense electromagnetic radiation in the wavelength range of 1–200 nanometers. It is intended that the scope of the invention be defined by the claims.

I claim:

1. A gas filled, electric pulse excited, longitudinal gas discharge, laser tube comprising:

a gas tight elongated cylindrical electrically insulating vessel having an inner wall and an axis, said vessel containing a metal cathode electrode and metal anode electrode disposed within, said cathode electrode is disposed at one end of the vessel said anode electrode is disposed at the other end of the elongated electrically insulating vessel, said electrodes are joined to the said elongated electrically insulated vessel;

a plurality of electrically conducting discs disposed generally perpendicular to the axis, said discs are disposed between said anode and cathode electrodes and are surrounded by said elongated electrically insulating vessel, said discs each having an aperture co-axially aligned with said tube axis, said discs are separated from one another by spacers constructed from a refractory electrical insulator, said spacers having an internal dimension greater than said axial aperture dimension and an external dimension less than an internal dimension of the insulating vessel, means for exciting the gas in said laser tube with a fast high peak current electrical pulse having a peak current density greater than 50,000 amperes per square centimeter and sufficient to produce an optical output below 200 nanometers.

2. Apparatus according to claim 1 wherein said discs are constructed from a refractory metal such as Molybdenum or Tungsten.

3. Apparatus according to claim 1 wherein said discs have additional apertures; said additional apertures being individually of smaller cross sectional area than said axial aperture, said additional apertures are separate from said axial aperture and are disposed between the axial aperture and the distal edge of the disc, whereby said additional apertures permit equalization of pressure differences caused by gas pumping.

4. Apparatus according to claim 1 wherein said means for extracting a laser beam comprises laser mirrors in direct contact with the laser gas, said mirrors are disposed about axis of the tube.

5. Apparatus according to claim 1 wherein said apertures are circular and the laser output beam is radially symmetric; said radial symmetry is in the laser beam intensity distribution and in the laser beam divergence.

6. Apparatus according to claim 1 wherein the laser output wavelength is below 30 nanometers in the soft Xray region of the electromagnetic spectrum.

7. Apparatus according to claim 1 wherein the construction materials of the entire discharge tube and the material used to join parts is heated to a temperature of 350 centigrade while maintaining vacuum integrity.

8. Apparatus according to claim 1 wherein said discs and said cathode and anode electrodes are constructed from refractory metals.

9. Apparatus according to claim 1 wherein the gas fill contains at least one gas species;

said gas species producing laser output during one discharge cycle and it's afterglow;

said gas species producing laser output at different wavelengths.

10. Apparatus according to claim 1 wherein a second gas is added to the active lasing gas to increase the magnitude of the laser power output due to the active lasing gas.

11. Apparatus according to claim 1 further including a source of at least one active laser gas at a pressure in excess of the operating pressure of the laser discharge tube;

said source of gas connected to but separated from the

main laser volume by a valve;

whereby said source of gas is used to replenish the gas in the main laser vessel and maintain the optimum pressure for maximum laser output should the gas in the main laser vessel become reduced in pressure.

12. Apparatus according to claim 11 further including a gas pressure sensor connected to the main laser volume;

whereby said pressure sensor is used to determine whenever the gas pressure in the main laser volume decreases below the optimum for maximum laser output.

13. Apparatus according to claim 12 further including a feed back control or microprocessor system to automatically maintain the gas pressure in the main laser volume at the optimum for maximum laser output;

said feedback controller can determine the gas pressure through said gas pressure sensor, said feedback controller capable of opening and closing said valve to add a controlled amount of gas to the main laser volume.

14. Apparatus according to claim 1 wherein said laser discharge tube is terminated on the optical axis with windows that are transparent at the laser wavelength.

15. Apparatus according to claim 1 wherein said discs are constructed from a plurality of materials, the material comprising the axial section of the disc in contact with the gas discharge being a refractory metal.

16. Apparatus according to claim 1 wherein said discs disposed adjacent to the said electrodes have axial bore aperture of larger diameter than the apertures in the discs disposed furthest from the anode and cathode electrodes, whereby said increased diameter apertures result in a discharge bore tapered at each end.

17. Apparatus according to claim 1 further including a volume of at least one active laser gas at the operating pressure of said laser discharge tube;

said source of gas connected to the main laser volume.

18. Apparatus according to claim 1 wherein one end of said laser discharge tube is terminated by a laser mirror and the other end is terminated by a vacuum flange, whereby said vacuum flange may couple the laser to a vacuum system or a chamber containing a gas which is transmitting to the laser output.

19. Apparatus according to claim 1 wherein the means for extracting pulsed laser output comprises both ends of the laser tube being open.

20. Apparatus according to claim 1 further including a liquid cooling jacket disposed about the outer diameter of said elongated electrically insulated tube.

21. A gas filled pulse excited longitudinal electric discharge laser vessel comprising;

a gas tight elongated electrically insulating vessel having an inner wall and an axis, said vessel containing a metal cathode electrode and metal anode electrode disposed within said gas tight elongated insulating vessel, said cathode electrode is disposed at one end of the vessel said anode electrode is disposed at the other end of the elongated electrically insulating vessel, said electrodes are joined to the said elongated electrically insulated vessel;

a plurality of electrically conducting thin plates disposed generally perpendicular to the axis said thin plates are disposed between the said anode and cathode electrodes and are surrounded by the said elongated electrically insulating vessel, said thin plates have a dimension in the direction perpendicular to the tube axis somewhat less than an inner dimension of the elongated insulating vessel, said thin plates each having an aperture co-axially aligned with the vessel axis, said thin plates are separated from one another by spacers constructed from a refractory electrical insulator, said spacers having an internal dimension greater than a aperture dimension and an external dimension less than an internal dimension of the insulating vessel, said thin plates and spacers are disposed between the anode and cathode electrodes;

means for electrically pulse exciting said tube with a high peak current pulse having a peak current density greater than 50,000 amperes per square centimeter and sufficient to produce an optical output below 200 nanometers.

* * * * *

RADIATION MODULATORS

April 21, 1959 F. H. LONDON 2,883,555

THICKNESS MEASURING APPARATUS WITH COMPENSATION FOR ATMOSPHERIC CONDITIONS

Filed May 28, 1956

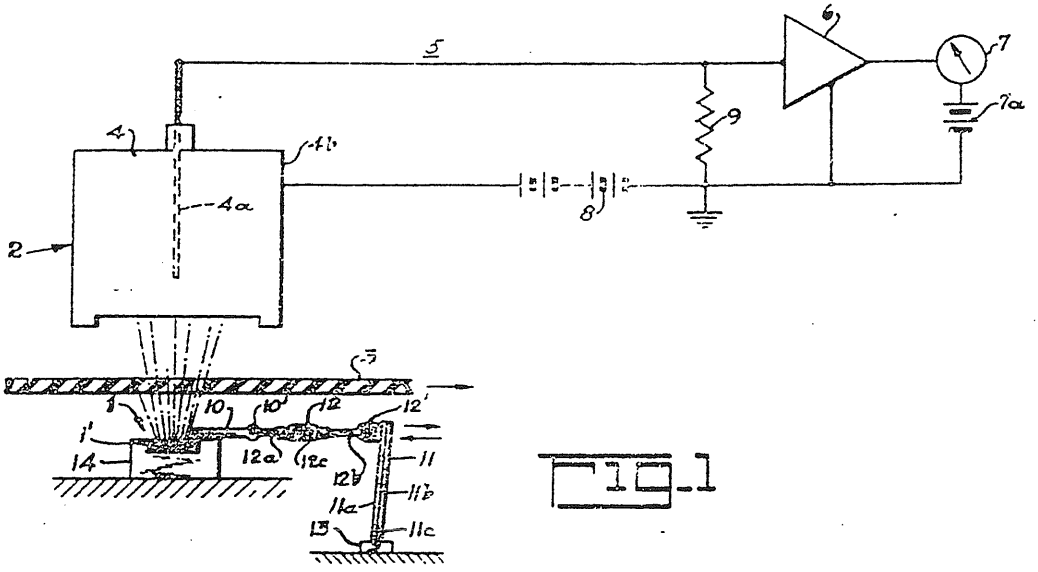

FIG. 1

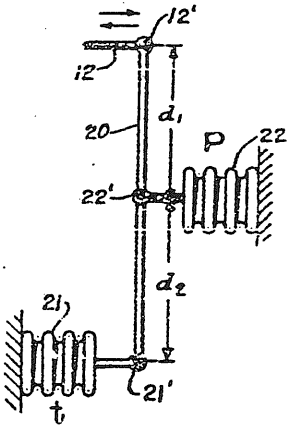

FIG. 3

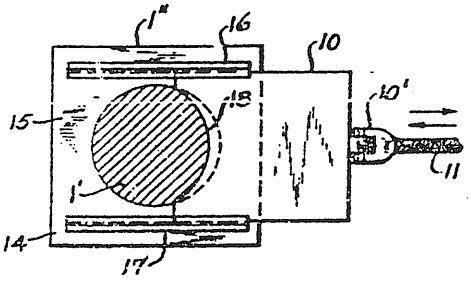

FIG. 2

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United States Patent Office 2,883,555 Patented Apr. 21, 1959

2,883,555

THICKNESS MEASURING APPARATUS WITH COMPENSATION FOR ATMOSPHERIC CONDITIONS

Fred H. London, New York, N.Y., assignor to Curtiss-Wright Corporation, a corporation of Delaware

Application May 28, 1956, Serial No. 587,506

8 Claims. (Cl. 250—105)

This invention relates to radiation measuring apparatus of the type commonly used for non-contact measurement of thickness or density of continuously produced strip material, and has for its principal object an improved and precise radiation measuring apparatus of the aforesaid character that is operative automatically to compensate errors due to variations in ambient atmospheric conditions, such as temperature and barometric pressure.

The thickness or density of continuously produced strip materials such as paper, plastics, metals, etc., has been indicated and/or controlled by radiation measuring apparatus wherein the material to be measured is subjected to penetrative radiation, such as from a source of beta or gamma radiation, and the unabsorbed radiation from the material is detected and measured for determining the thickness or density at the point of measurement. Apparatus of this character has been developed to such a high degree of accuracy that differences in radiation absorption incident to change in mass of the gap medium between the source and detector (which may be due to variations in ambient temperature or barometric pressure) cause material errors in measurement. For example, if it be assumed that the gap medium is air and that ambient temperature is at predetermined normal or reference value and that barometric pressure is higher than normal, then the density of the air gap, i.e. its mass, will be slightly greater than normal, thereby resulting in increased radiation absorption in the air gap with correspondingly less radiation received at the detector. Accordingly, the measurement of the material will be erroneous to the extent that greater thickness or density than for the actual case will be indicated. The same general result obtains where the ambient temperature is lower than normal. Conversely, a decrease in mass of the air gap results in increased radiation received at the detector, thereby falsely indicating that the material has less thickness or density than is actually the case.

In accordance with the present invention, variation in gap medium absorption due to ambient atmospheric conditions is compensated by means responsive to variations in the aforesaid conditions for automatically stabilizing the effective radiation through the gap medium. In a specific embodiment of the invention, the atmospheric condition responsive means is effective to control the amount of radiant flux received thereby to compensate for variation in mass of the gap medium.

The invention will be more fully set forth in the following description referring to the accompanying drawing, and the features of novelty will be pointed out with particularity in the claims annexed to and forming a part of this specification.

Referring to the drawing, Fig. 1 is a partly diagrammatic and schematic illustration of a radiation measuring system embodying the present invention having means for compensating error due to change in temperature of the gap medium; Fig. 2 is an enlarged detailed top plan view of the radiation source and radiation flux control

means illustrated in Fig. 1; and Fig. 3 is a modified form of the system shown in Fig. 1 for temperature and pressure compensation.

The radiation measuring system schematically illustrated in Fig. 1 comprises a source of radiation generally indicated at 1, and a radiation detector 2 of suitable type spaced from the source as indicated, by an air gap. Within the air gap is disposed material to be measured in respect to thickness or density, as the case may be. In the present instance the material 3, which may be paper, plastics, etc., is of strip form arranged as it is produced continuously to move through the gap. In this type of system the radiation from the source 1, which may be a radioactive isotope 1' emitting beta rays, penetrates the strip material where it is partially absorbed, depending on the mass of the material, and the unabsorbed radiation enters the detector 2.

By way of example the detector 2 may comprise an ionization chamber 4 of well-known type having a probe electrode 4*a* and a conducting wall 4*b* forming the other or positive electrode. The electrodes are connected in conventional manner by circuitry 5 to an amplifier 6 which energizes a calibrated indicator 7. A suitable D.C. potential bucks out the quiescent D.C. output potential of amplifier 6, so that the deflection of indicator 7 is related directly to change in output potential with respect to the quiescent potential, rather than to ground potential, whereby its sensitivity is improved. A high D.C. potential indicated at 8 is impressed on the wall electrode 4*b* and is connected as illustrated to a grounded resistor 9 which completes an external circuit with the electrode 4*a*. The lower wall of the ionization chamber 4 may be provided with suitable sealed apertures (not shown) through which radiation enters the chamber causing ionization with resulting current flow through the external circuit including the resistor 9 according to the intensity of radiation entering the chamber. Thus, the amplifier 6 is responsive to the potential difference across resistor 9 and, since this potential difference is proportional to the radiation received by the detector, the indicator 7 can be calibrated in terms thereof.

Although a simple indicating system is illustrated, it should be understood that the signal from the amplifier 6 can be used either to indicate the departure of the thickness or density of the material 3 from a predetermined value or may also by well-known means control a recorder, as well as means governing the production of said material so as to correct the error in thickness or density.

In systems heretofore used, the amount of radiant flux received in the detector is generally fixed for a given operation at a predetermined magnitude so that when material of standard thickness or density is interposed in the gap, the indicator 7 reads zero. Accordingly any deviation from the standard in either direction results in a signal of corresponding sense at the indicator 7. It should be understood that the arrangement of the radiation source 1, detector 2 and material 3 may be varied according to the method preferred; for example, instead of being at opposite sides of the material 3 as shown the source 1 and detector 2 may be at the same side of the material and positioned so that unabsorbed radiation is reflected or "back-scattered" into the detector.

As previously stated, the gap medium (air in the present instance) may have different absorption capacity under varying ambient atmospheric conditions, assuming that the air gap is fixed, and that the radiation is constant. That is, the amount of unabsorbed radiation flux entering the detector 2 depends on the mass of the gap medium as well as the mass of the material being measured. In accordance with the present invention and in the preferred manner, a movable radiation shield or

shutter 10 is positioned generally over the source of radiation 1. The shutter is made of a material suitable for diverting a portion of the radiant flux emitted or transmitted as by reflection, absorption or refraction. The amount of diverted flux varies depending on the shutter position. A means responsive to atmospheric conditions is arranged to position the shutter so as to compensate for the measurement error due to change in mass of the gap medium.

To this end there is shown in Fig. 1 a device 11 of well-known bimetal type that is responsive to temperature variations so as bodily to move shutter 10 relative to source 1 by means of an interconnecting link or lever 12. The device 11 is fixed at one end as at 13 and its opposite free end is pivotally interconnected with an end of lever 12 at 12'. An end '0' of the shutter 10 is pivotally interconnected with the other end of lever 12, so that with motion of the device 11 motion is imparted to shutter 10.

Device 11 comprises two metallic strips 11*a* and 11*b* having unequal coefficients of thermal expansion. The strips are joined together along the common surface 11*c*. Specifically the coefficient of strip 11*a* is lower than the coefficient of strip 11*b*, so that with an increase of temperature the device 11 warps in a counter-clockwise direction, thereby imparting a leftward movement to shutter 10. Shutter 10 is caused to divert a portion of the radiant beam greater than that diverted at normal ambient temperature. A greater diversion is proper to diminish the radiation received at detector 2, which in the absence of temperature compensation would be too great as pointed out hereinabove. Conversely with a decrease in ambient temperature the device 11 warps in a clockwise direction, thereby imparting a rightward movement to the shutter 10 and increasing the radiation received in detector 2 to the standard amount.

Lever 12 comprises two threaded end-members 12*a* and 12*b* which are threadably secured to a central member 12*c*, a turnbuckle, provided to permit adjustment of the effective lengths of members 12*a* and 12*b* with reference to the operating characteristics of device 11, so that movement of the shutter is in proper relation to temperature changes.

Referring to Fig. 2, the source 1 comprises a base 14 which has a recessed surface 15 in which the isotope 1' is disposed. The shutter 10 is of generally rectangular sheet form. It is constrained to lateral sliding movement by means of guides 16 and 17 which are secured to the surface 15 and engage a pair of parallel sides of the rectangle defining the shutter. An end 18 of the shutter which is opposite to the end 10' lies generally over the isotope 1' and is of curved shape so as to provide still further correlation of the diversion of radiation with the characteristics of the device 11. The curved shape serves for the further purpose of substantially preserving the general geometry of the apparatus and therefore its calibration irrespective of shutter position.

If it is desired to still further perfect the preservation of the general geometry, an opposite shutter of similar construction to shutter 10 may be included in symmetrical arrangement and disposition thereto with respect to the isotope 1'. The shutters may be caused to converge or diverge from isotope 1' by suitable simultaneous actuating means responsive to movement of device 11.

Fig. 3 illustrates in simple form an arrangement of temperature and pressure compensating means for controlling the radiation source. In this arrangement one end of link 13 is pivotally interconnected with one end of another suitable linkage or lever 20 at 13'. Lever 20 is actuated jointly by suitable temperature and pressure responsive devices indicated at 21 and 22 respectively. The bellows 21 which contains a suitable liquid in both liquid and vapor phases is temperature responsive and is connected to the lever at pivot 21', and the

bellows 22 which is evacuated so as to be responsive to barometric pressure is connected to the floating pivot or fulcrum 22' of the lever 20. The lever arms d_1 and d_2 are selected with reference to the operating characteristics of the two bellows so that movement of the shutter is in proper relation to temperature and/or pressure changes.

It will therefore be seen that in practicing my invention as illustrated in Fig. 3 the radiation flux may be controlled according to the joint effects of ambient temperature and barometric pressure changes so as to compensate for change in mass of the gap medium due to the aforesaid conditions.

As used herein insofar as respects the response of detector 2, radiation, intensity of radiation or effective radiation is a measure of that quality of the radiant energy which is effective in causing ionization in the radiaton detector 2, and flux or radiant flux is a measure of the radiant energy emitted by the source 1 or transmitted to or received by detector 2. Radiation, intensity of radiation or effective radiation, therefore, depends on the flux actually received by detector 2 as well as on the distance separating the detector 2 from the source 1. On the other hand flux is independent of the separating distance.

It should be understood that this invention is not limited to specific details of construction and arrangement thereof herein illustrated, and that changes and modifications may occur to one skilled in the art without departing from the spirit of the invention.

What is claimed is:

1. Apparatus for measuring the thickness or density of continuously produced strip material comprising a source of radiant energy disposed so that the material to be measured is subject to penetrative radiation from said source, a radiation detector disposed at a substantially fixed mean distance from said source and in operative relation to said material and said source for receiving radiation unabsorbed by said material, adjustable means for controlling the amount of radiant flux received by said detector, and means responsive to variations in an atmospheric condition for adjusting said control means thereby to compensate for variation in gap medium absorption due to change in mass of the gap medium between said source and detector.

2. Thickness measuring apparatus as specified in claim 1 wherein the last-named means comprises means subject to contraction and expansion in response to ambient temperature variation.

3. Thickness measuring apparatus as specified in claim 1 wherein the last named means comprises means subject to contraction and expansion in response to atmospheric pressure variation.

4. Measuring apparatus as specified in claim 1 wherein the last-named means comprises two devices functioning jointly to control the amount of transmitted radiant flux, said devices comprising an ambient temperature responsive device and a barometric pressure responsive device.

5. Thickness measuring apparatus as specified in claim 1 wherein the control means is effective to decrease the amount of radiant flux entering the gap from the source in accordance with increase in ambient temperature and vice versa.

6. Thickness measuring apparatus as specified in claim 1 wherein the control means comprises radiation shutter means positioned in the radiant beam emanating from the source by the atmospheric condition responsive means so as to control the amount of flux received by the detector.

7. Apparatus for measuring the thickness or density of continuously produced strip material comprising a source element for producing radiant energy disposed so that the material to be measured is subject to pene-

trative radiation from said source, a radiation detector element disposed in operative relation to said material and said source element for receiving radiation unabsorbed by said material, radiation shutter means interposed of said elements for diverting a portion of the radiant flux therebetween, and means responsive to variations in an atmospheric condition for causing relative movement of said shutter and one of said elements thereby to compensate for variation in gap medium absorption due to change in mass of the gap medium between said source and detector.

8. Apparatus for measuring the thickness or density of continuously produced strip material comprising a source of radiant energy disposed so that the material to be measured is subject to penetrative radiation from said source, a radiation detector disposed in operative

relation to said material and source for receiving radiation unabsorbed by said material, radiation shutter means interposed between said source and detector for diverting a portion of the radiant flux therebetween, a bimetallic element warpable responsive to change in ambient temperature, and means responsive to warping of said bimetallic element for positioning said shutter means thereby to compensate for variation in gap medium absorption due to change in mass of the gap medium between said source and detector with change in ambient temperature.

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March 6, 1962 S. WANETICK 3,024,364

RADIO-ACTIVE TRANSDUCER

Filed Aug. 6, 1959

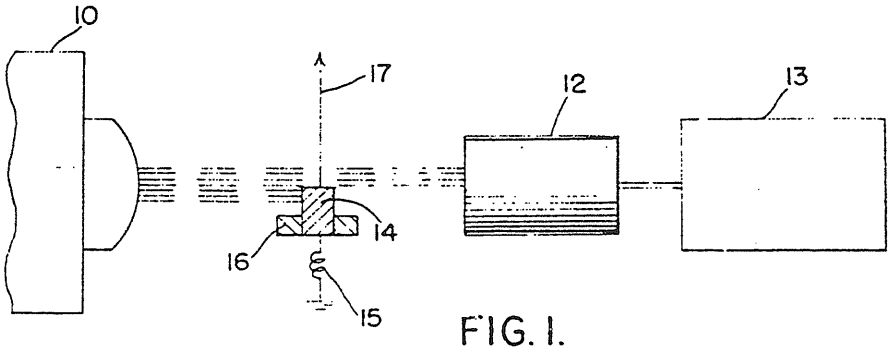

FIG. 1.

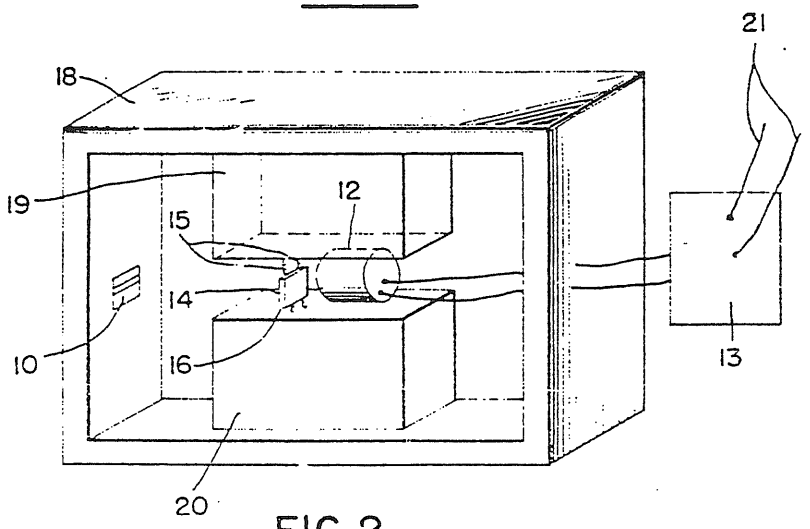

FIG. 2.

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United States Patent Office

3,024,364
Patented Mar. 6, 1962

3,024,364
RADIO-ACTIVE TRANSDUCER

Saul Wanetick, Philadelphia, Pa., assignor to the United States of America as represented by the Secretary of the Army

Filed Aug. 6, 1959, Ser. No. 832,125
1 Claim. (Cl. 250—83.3)
(Granted under Title 35, U.S. Code (1952), sec. 266)

The invention described herein may be manufactured and used by or for the Government for governmental purposes without the payment to me of any royalty thereon.

This invention relates to transducers such as are operable to measure change in the velocity of a moving object, and has for its purpose to provide an improved transducer or accelerometer which is more rugged in structure and is less sensitive to change in its environment than the transducers theretofore available.

Many presently available transducers are operable to produce an effect dependent on their attaining a predetermined velocity. Such devices generally have not been altogether reliable in operation for the reason that their sensitivity is affected by variations in temperature. capacitance or the transverse forces they are subjected to during their operation. In accordance with the present invention these difficulties are avoided by the provision of a transducer which is rugged in structure, and depends for its operation on a source of radioactive emission.

The invention will be better understood from the following description when considered in connection with the accompanying drawings and its scope is indicated by the appended claim.

Referring to the drawings:

FIG. 1 is an explanatory diagram relating to the operation of the invention, and

FIG. 2 is a detailed showing of the invention.

FIG. 1 shows a radioactive source 10 from which a collimated beam 11 of radioactive particles is directed toward a scintillation detector 12. This detector has its output connected to a counter 13 and may be in the form of a phosphor and a photomultiplier mounted within a tubular member in a manner well understood by those skilled in the art.

Between the source 10 and the scintillator tube 12 is a shield 14 which is resiliently supported by means such as a spring 15. This shield consists of a material such as aluminum which absorbs and obstructs the passage of radioactive particles. To make it responsive to velocity change, it is fixed to a mass 16.

Assuming these various parts to be assembled into a unitary structure as hereinafter indicated it can be seen that the shield 14 intercepts less of the beam 11 when

the structure is accelerated in the direction of the arrow 17 and more of the beam when the structure is accelerated in the opposite direction. From this it follows that the number of particles reaching the scintillator is a measure of the acceleration imparted to the object. The number of these particles are registered on the counter 13 which may function to control an electric circuit or produce some other effect in response to a predetermined count.

FIG. 2 shows the above-identified parts as mounted in an enclosure 18. In this arrangement, the source 10 is shown as mounted on the wall of the enclosure. It may consist of a capsule which is associated with a narrow slit to form a narrow beam of radio-active particles.

Fixed to the top and bottom of the enclosure are supports 19 and 20. Mounted between these supports through the medium of springs 15 are the shield 14 and the mass 16 previously mentioned. Also mounted between the supports 19 and 20 are the scintillation detector 12. Obviously the detector and counter may be mounted in any other convenient location and the counter output leads 21 may be connected to a device which is to be operated upon the attainment of a predetermined acceleration, this device being located inside or outside the enclosure.

As will be apparent to those skilled in the art, the herein described device can be compact, and in a form which can take large overloads without breakage. It has the additional advantages that it is substantially independent of temperature variation, and is free from capacitance and transverse effects.

I claim:

An accelerometer for measuring acceleration of a mass in a direction normal to a path of a radiant energy beam, said accelerometer including a casing, a radio active source for transmitting a narrow beam of radio-active particles within said casing, a detector mounted in said casing for receiving energy from said source, a shield capable of absorbing energy from said source, a resilient support arranged normally to maintain said shield in the path of said beam, and a mass arranged with said support to move with said shield in a direction normal to said beam to an extent which is dependent on the acceleration of said mass and shield.

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April 21, 1964 P. P. SOROKIN ETAL 3,130,254

OPTICAL MASER HAVING TERMINAL LEVEL ABOVE GROUND STATE

Filed Dec. 5, 1960 4 Sheets-Sheet 1

FIG. 1

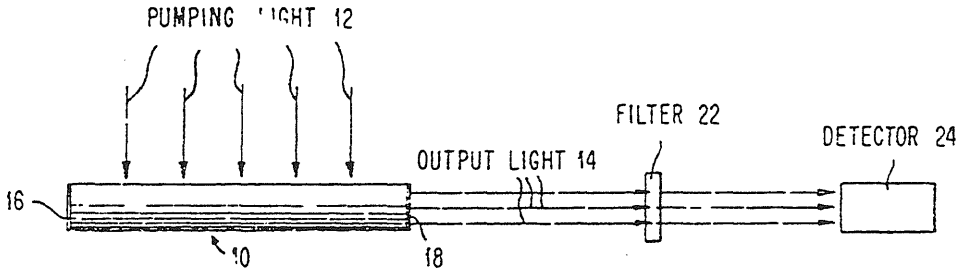


FIG. 2

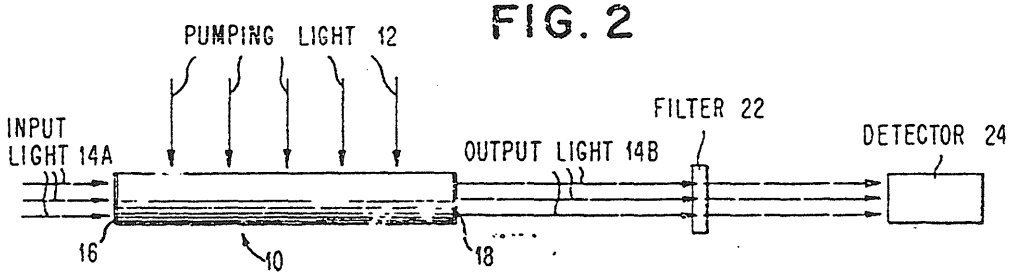
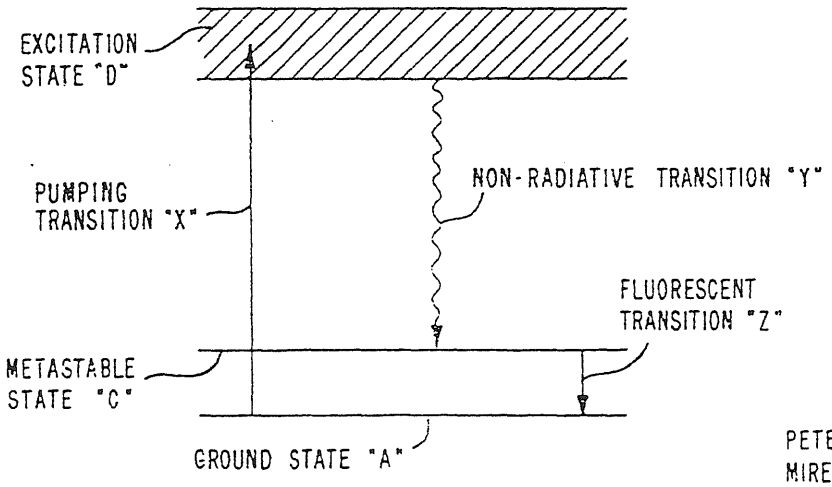


FIG. 3



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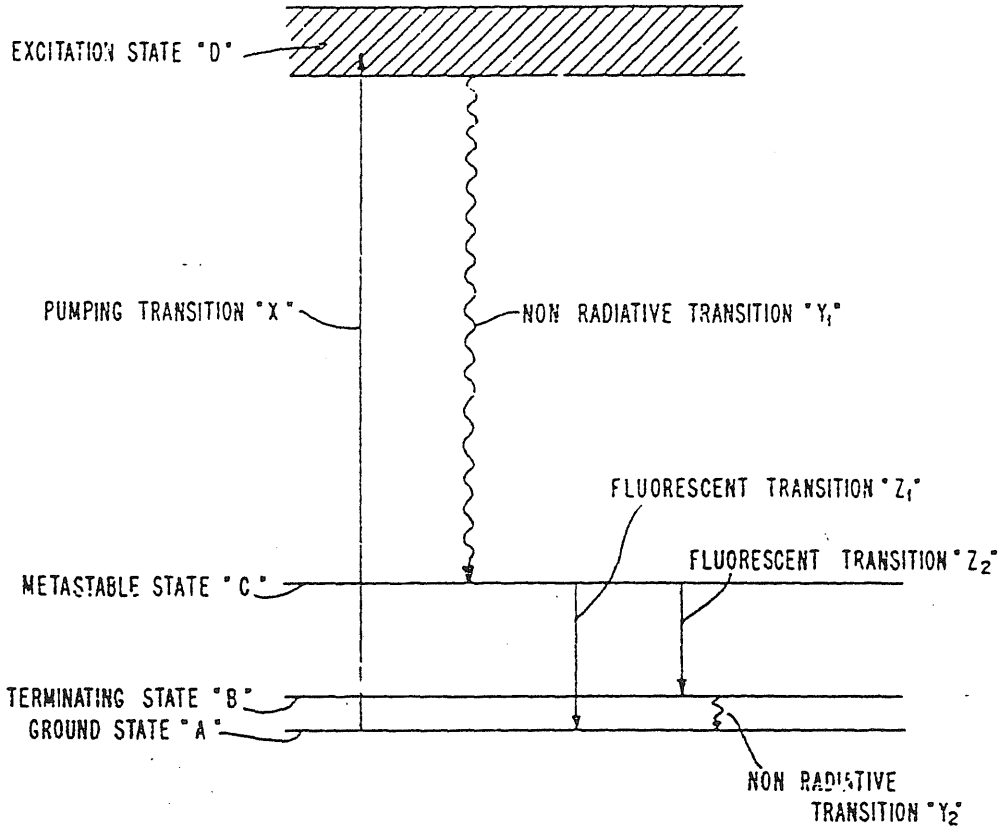
EXCITATION STATE "D"
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NON RADIATIVE TRANSITION "Y1"
FLUORESCENT TRANSITION "Z1"
FLUORESCENT TRANSITION "Z2"
METASTABLE STATE "C"
TERMINATING STATE "B"
GROUND STATE "A"
NON RADIATIVE TRANSITION "Y2"

FIG. 4

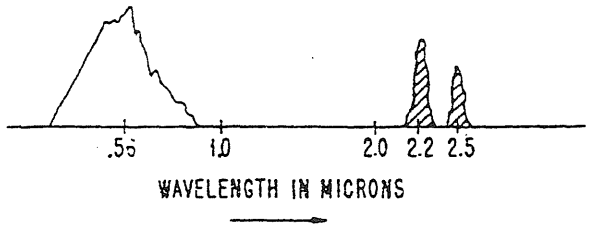

.56
1.0
2.0
2.2
2.5
WAVELENGTH IN MICRONS

FIG. 5

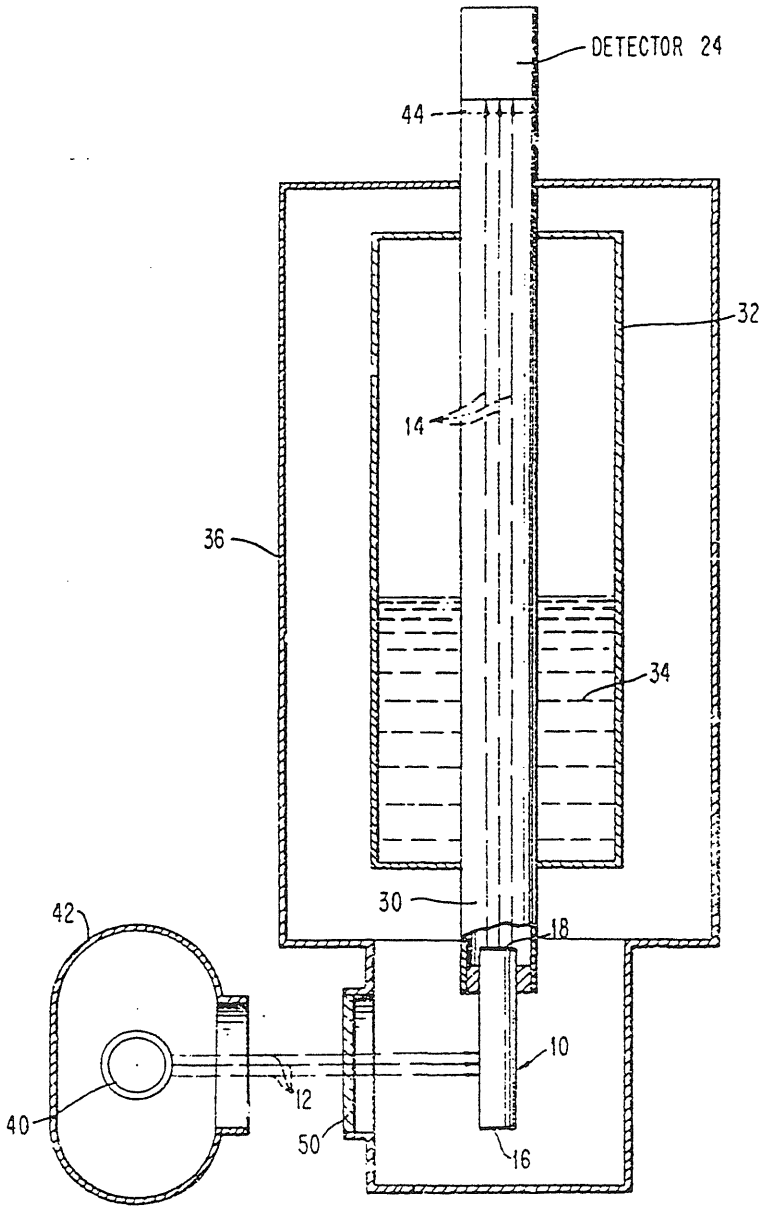


FIG. 6

FIG. 7A

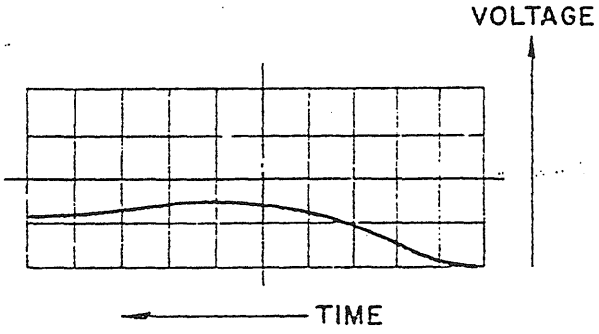


FIG. 7B

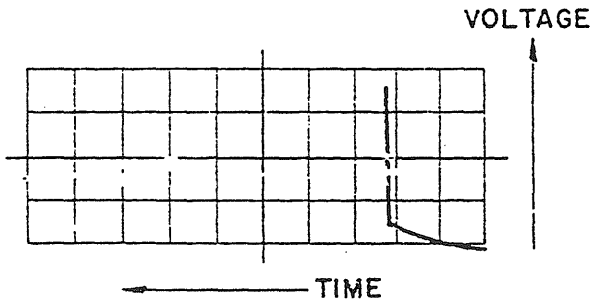
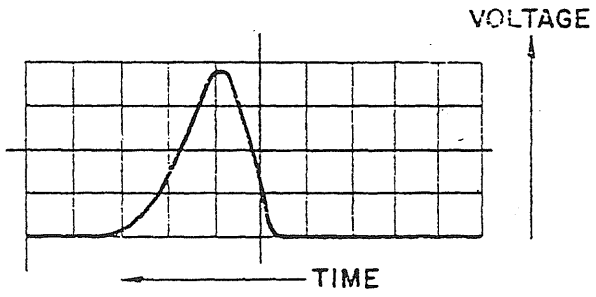


FIG. 7C



United States Patent Office 3,130,254 Patented Apr. 21, 1964

3,130,254

OPTICAL MASER HAVING TERMINAL LEVEL ABOVE GROUND STATE

Peter P. Sorokin, Chappaqua, and Mirek J. Stevenson, Briarcliff Manor, N.Y., assignors to International Business Machines Corporation, New York, N.Y., a corporation of New York

Filed Dec. 5, 1960, Ser. No. 73,878
24 Claims. (Cl. 88—1)

The present invention relates to masers and, more particularly, to optical masers which depend for their operation upon the properties of trivalent uranium.

The term optical maser is used to describe devices which, by stimulated fluorescent emission produce radiation in the infrared, visible and ultraviolet portions of the electromagnetic wave spectrum. Devices of this type are capable of producing radiation which is highly directional, monochromatic and coherent. In recent years, a large amount of research and development work has been expended in attempting to develop devices of this type, as is evidenced by the patent and publications cited below.

U.S. Patent No. 2,929,922, issued March 22, 1960, to Schawlow et al. Schawlow and Townes, Physical Review, vol. 112, page 1940 (December 1958). T. H. Maiman, Nature, vol. 187, page 493 (August 1960).

T. H. Maiman, British Communications and Electronics, vol. 7, page 674 (1960). R. J. Collins et al., Physical Review Letters, vol. 5, page 303 (October 1960).

However, up to this point, only one satisfactory optical maser has been developed. The maser material utilized is ruby and produces, by stimulated emission, outputs in the visible portion of the light spectrum, specifically, in the red, having a wavelength of about 6940 angstroms.

By proper design of the maser cavity formed by the ruby crystal, it is possible to produce not only monochromatic radiation at this wavelength, but also radiation which is coherent and highly directional.

However, no optical masers have been available which are capable of producing outputs at other than this particular frequency. Further, in the operation of the ruby maser, the fluorescent transition stimulated to produce the desired emission terminates in the ground stated and, therefore, it is necessary to supply a very high intensity input pumping energy to produce the desired stimulated emission.

In accordance with the principles of the present invention, improved stimulated emission devices are provided which are capable of producing monochromatic, coherent and highly directional outputs at wavelengths which were not previously realizable and, further, to produce such outputs with a much smaller amount of input energy being supplied to the maser device. These inputs are achieved by utilizing to advantage the properties of trivalent uranium, which, when used as an impurity or doping agent in a proper crystalline host lattice, provides improved maser operation. More specifically, crystals doped with trivalent uranium exhibit strong absorption bands in the visible portion of the spectrum and, therefore, may be pumped easily with sources of visible light; trivalent uranium doped crystals exhibit extremely sharp fluorescent lines, thereby enabling achievement of maser operation; trivalent uranium doped crystals exhibit fluorescent transitions between two energy states, both of which are above the ground state for the trivalent uranium ions in the material, thereby lessening by a large amount the input energy required to initiate stimulated emission in the crystalline material. Further, trivalent uranium doped crystals may be fabricated so that the fluorescent line, at which the stimulated emission is produced, is in the infrared range.

More specifically, in accordance with the principles of the present invention, crystalline materials having a cubic symmetry and, therefore, an isotropic index of refraction have been found to be particularly adapted to maser applications when doped with small amounts of trivalent uranium. The cubic symmetry is advantageous since, with crystalline material having an isotropic index of refraction, it is possible to fabricate large crystals in the geometries in which oscillations can be produced in a desired mode without appreciable losses, even though there be some disorientation of the crystal in the cavity geometry. The alkaline earth fluoride, which include calcium fluoride, barium fluoride, and strontium fluoride, have been found to be particularly suitable host crystals, into which trivalent uranium is introduced as an impurity to produce improved stimulated emission type devices. A specific example, calcium fluoride, when doped with small amounts of trivalent uranium, is capable of producing a very high intensity monochromatic, coherent light output in the infrared region which requires for the production of the output only a relatively small amount of input pumping energy.

Therefore, it is an object of the present invention to provide improved stimulated emission type devices, more particularly, devices of the type which are termed optical masers.

Another object is to provide an optical maser capable of producing an output in the infrared.

Still another object is to provide an optical maser requiring only a relatively low amount of input energy to produce stimulated emission, and oscillation in a maser cavity.

Still another object is to provide improved optical masers which produce outputs in the form of monochomatic coherent light by stimulated transitions in the crystalline material of ions between the two energy states, both of which are above the ground state for the ions in the material.

Still another object is to provide improved optical masers employing crystals doped with trivalent uranium.

A further object is to provide improved optical masers of the above described type wherein the host crystal is cubic.

It is a still further and more specific object to provide improved optical masers formed of crystals of one of the alkaline earth fluorides, that is, calcium fluoride, strontium fluoride and barium fluoride, doped with a small amount of trivalent uranium.

The foregoing and other objects, features nad advantages of the invention will be apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings.

In the drawings:

FIG. 1 is a schematic diagram of an optical maser used as a generator.

FIG. 2 is a schematic diagram of an optical maser used as an amplifier.

FIG. 3 is an energy level diagram indicating the transitions which occur top roduce optical maser operation in a material wherein the stimulated emission transition terminates in the ground or lowest energy state for the ion in the material.

FIG. 4 is an energy level diagram depicting the characteristics of an embodiment of a maser material fabricated in accordance with the principles of the present invention.

FIG. 5 shows a certain portion of the absorption and the fluorescent spectrum of the material whose energy level characteristics are depicted in FIG. 4.

FIG. 6 is a somewhat schematic representation of one embodiment of the subject invention wherein a calcium fluoride crystal doped with trivalent uranium is main-

tained at a temperature close to liquid helium temperature and operated to produce a monochromatic coherent infrared output.

FIGS. 7A, 7B and 7C depict outputs obtained with an oscilloscope connected to the detector of the embodiment shown in FIG. 6.

Now referring to the drawings in detail, FIGS. 1 and 2 show optical maser devices used in application shown in the prior art. The energy level diagram of FIG. 3 is representative of the internal operation of prior art maser devices, such as ruby masers. These figures are included and a detailed description of their operation is given both to illustrate applications in which optical masers have been used, and to provide a basis for a clearer understanding of the basic principles of optical maser operation in general, and of the invention to which this application is directed.

FIG. 1 shows an embodiment of an optical maser used as a generator of electromagnetic waves. In this figure, 10 generally designates the optical maser cavity to which input pumping light, represented by the arrows 12, is applied to produce an output, represented by the arrows 14, which is both coherent and monochromatic. The cavity 10 is cylindrical in shape and is provided at opposite ends with reflective surfaces 16 and 18. Each of these surfaces is made to reflect some 98½% of the light incident thereon, and to transmit approximately 1.5% of the incident light. Where the device is to be used solely as a generator, reflecting surface 16 may be completely opaque.

The cavity 10 may be formed of a crystal such as ruby, as taught by the prior art, or of a material of the type to which the present invention is directed. Also it has been proposed to construct maser cavities using a tubular container containing a vapor having the characteristics required to produce the optical maser effect.

The manner in which optical maser devices operate may be best understood by considering FIG. 3, which is a diagram illustrating the energy states within the maser material, as well as the various transitions which occur to produce the optical maser action. In this figure, three different energy states for the ions present in maser material are shown, specifically, a ground state A, a metastable state C and an excitation state D, which is really a broad band of states into which ions can be relatively easily pumped from the ground state. When the maser material is in the quiescent state, that is, in the absence of pumping, essentially all of the ions in the material are in the ground state A. When the pumping input, represented by arrows 12 in FIG. 1, is applied, certain of these ions undergo a pumping transition illustrated by the arrow X to the excitation band D. In order for this transition to occur, the pumping light applied as an input must include light at the frequency necessary to pump ions from ground state A to the excitation band D. This frequency is determined by the absorption characteristics of the maser material and it is preferable if this frequency is in the visible portion of the spectrum. During this pumping operation from ground state A to the excitation state or band D, energy is absorbed in the maser material. The ions, once they are pumped into the excitation band D, undergo a non-radiative transition represented by arrow Y to a metastable state C. By non-radiative, it is meant that during this transition, no fluorescence is produced, but rather, the energy associated with the transition is dissipated in lattice vibrations within the crystalline material. The ions in the metastable state C, after this non-radiative transition, then go through a fluorescent transition, represented by the arrow Z, back to the ground state A. During this transition, a light output is produced at a frequency determined by the fluorescent characteristics of the maser material. For example, the energy level diagram of FIG. 3 in which the fluorescent transition terminates in the ground state A is the type of transition utilized in ruby masers of the prior art which produce outputs at a wavelength of about 6940A.

As long as the input pumping light is maintained below a predetermined threshold, the number of ions pumped to excitation state D, which then undergo a non-radiative transition Y back to state C and finally a fluorescent transition Z back to the ground state, is too small to produce stimulated emission in the crystal and oscillation in the cavity. The output produced by the material under these conditions is referred to as spontaneous emission.

When, however, the pumping light input is increased to an intensity above a predetermined threshold, sufficient ions are moved from the ground state A through excitation state D and to metastable state C, and undergo fluorescent transitions between this state and the ground state A to produce stimulated emission of further ions between these two states. When this stimulated emission is sufficient to overcome losses in the cavity, oscillations between surfaces 16 and 18 build up to produce a high intensity monochromatic coherent light output as represented by the arrows 14 in FIG. 1. This phenomenon necessary for the optical maser effect, which is referred to as stimulated emission, is achieved when a sufficient population inversion is achieved between the low energy ground state A and higher energy metastable state C. When the pumping input produces a sufficient amount of this stimulated emission, light at the characteristic wave-length propagating in a mode between surfaces 16 and 18 actually picks up energy as it propagates. When this occurs, oscillations in this mode occur to build up high intensity, monochromatic, coherent light in the cavity.

The minimum requirement for producing this oscillation is, as stated above, that there be a population inversion between the states A and C, sufficient to overcome losses in the cavity. The maser material in its quiescent state has practically all of its ions in its low energy or ground state A. In order to achieve a population inversion, that is a condition where there are more ions in the higher energy state C than in the lower energy ground state A, it is necessary that the population of the ground state A be depleted and the population of the metastable state C be increased. This is accomplished by the pumping operation, whereby the ions are pumped to the excitation state D from which they leak back in non-radiative transitions to the metastable state C. Each of these ions then undergoes a fluorescent transition from state C to state A, producing a light output at a frequency characteristic of transitions between these two states. This light energy at this frequency, once produced, is available to stimulate further transitions between the same two states C and A. These transitions may be from the ground state A to the metastable state C which is an absorption type transition or from the metastable state C to the ground state A to produce still more fluorescence. As the population of state C, relative to state A, is increased by the application of the pumping energy, the probability is also increased that the further transitions from state C to state A will be further fluorescent transitions, producing more light, rather than absorption transitions. When this population inversion reaches the point that the stimulated fluorescent radiation between states C and A have sufficient power to overcome any losses in wave propagation longitudinally between and at reflecting surfaces 16, 18 and oscillations occurs and continues in the crystalline maser.

As stated above, each of the transitions from state C to state A is at a particular frequency determined by the material itself and, therefore, the light propagating in the maser of FIG. 1, between electrodes 16 and 18, is at this particular frequency and is highly monochromatic. Further, since any light produced in any direction other than perpendicular to the surfaces 16 and 18 is allowed to pass through the side walls of the maser crystal or is absorbed thereat, the light oscillating back and forth be-

tween these surfaces is highly coherent. In the construction shown in FIG. 1, assuming that the surface 16 is completely opaque, and the surface 18 transmits 1.5% of the incident light, this small portion of the oscillating light in the cavity passes through surface 18 to produce a highly monochromatic coherent light output represented by the arrows 14. This output is applied to a filter 22, which filters all light except that at the desired frequency, and is then applied to a detector 24.

The device of FIG. 1 is a generator of electromagnetic waves since its function is to produce monochromatic coherent light at a predetermined frequency in response to the energy applied in the form of a light input represented by the arrows 12. The device of FIG. 2 is similar in construction to that of FIG. 1, but is more aptly termed an amplifier since its function is to amplify the intensity of a light input represented by arrows designated 14A during propagation in the cavity 10 and to produce the amplified output at the right hand side of the cavity as represented by the arrows 14B. For this type of operation it is necessary that both of the surfaces 16 and 18 transmit at least a portion of the light incident thereon. When operated in this mode, the pump energy, represented by the arrows 12, has an intensity below the threshold intensity so that, of and by itself, it is not sufficient to produce oscillation in the cavity. As a result, in the absence of light applied at the left hand side of the structure as represented by arrows 14A, only a low intensity output, produced primarily by spontaneous emission, is available at the right hand side of the structure. As explained above, in order to produce stimulated emission from the metastable state C to the ground state A, it is necessary that light waves having a predetermined frequency be present in the cavity. This frequency is characteristic of transitions between these two states. Therefore, the input light energy, represented by the arrows 14A, is of this characteristic frequency. The added energy applied to the device by this light input is sufficient to begin the process of stimulated emission, and thereby amplify the incoming signal. There is then available at the surface 18 an output of high intensity, monochromatic, coherent light 14B, which is an amplified version of the input represented by arrows 14A. This amplified output is passed through the filter 22 to a detector 24.

It should be apparent that the devices of FIGS. 1 and 2 may be combined with the output of light generator of FIG. 1, represented by arrows 14, applied as an input to the amplifying device of FIG. 2. Further, as is known in the prior art, represented by the above cited Patent 2,929,922, the output structure may be designed to include in place of the filter 22, a pair of double convex lenses separated by an absorptive sheet having an aperture lying in the focal place of the lens nearest the cavity. In this way, only the energy at the desired output frequency is passed through the aperture to the second lens which reconverts the energy at the desired frequency to a plane wave which may be radiated as an input to a detector, or as an input to an amplifier such as is shown in FIG. 2.

FIGS. 4 and 5 represent the characteristics of one embodiment of an optical maser fabricated in accordance with the principles of the present invention. FIG. 4 is an energy level diagram representing the various energy states of the ions in the maser material, and FIG. 5 is a partial representation of the spectrum for the material. Referring first to FIG. 4, this energy state diagram includes four states, a ground state A, a terminating state B, a metastable state C and an excitation state D. Maser operation is achieved in a device having the energy level characteristics represented in FIG. 4 by applying input light energy to pump ions from the ground state A to the excitation state D. During this pumping operation, energy is absorbed by the maser material and these ions undergo a non-radiative transition represented by the arrow Y_1 to the metastable state C. From this point, spontaneous emission takes place as the ions undergo a transition from state C to the terminating state B, represented by arrow Z_2, and also from state C to the ground state A, represented by arrow Z_1. In the operation of the maser to produce the desired monochromatic coherent light output, the fluorescent transition from metastable state C to the terminating state B is employed and, it is in this transition that stimulated emission is built up to produce the desired oscillation in the cavity.

Referring to FIG. 5, which shows a portion only of the spectrum of the maser material whose energy level diagram is depicted in FIG. 4, the shaded areas at 2.2 and 2.5 microns represent fluorescent lines for the material. These fluorescent lines at 2.2 and 2.5 microns correspond, respectively, to the transition from the metastable state C to the ground state A and the transition from the metastable state C to the terminating state B. The band depicted in FIG. 5, centered at 0.56 micron, represents a typical excitation state which is evident as a wide band strong absorption in the maser material. This absorption at .56 micron, is in the green range of visible light and, therefore, the input pumping light applied to a maser device such as shown in FIGS. 1 and 2, using material having the characteristics depicted in FIGS. 4 and 5, includes visible light in the green wave band.

The basic difference betwen the characteristics of the maser material of FIG. 4, which represents one embodiment of the invention to which this application is directed, over those of the prior art as shown in FIG. 3, is that the stimulated emission is produced between states C and B, rather than between state C and ground state A to produce the desired maser operation. As was pointed out above, when the maser is in a quiescent state, that is in the absence of input pumping energy, the population of the various states is such that almost all of the ions in the material are in the ground state A. Further, in order to produce the desired stimulated emission and resulting oscillation to realize a high intensity coherent output, it is necessary to supply sufficient energy to achieve a population inversion between the two states which produce the fluorescent transitions at the output frequency. Where these transitions are produced from a metastable state C to a ground state A, as shown in FIG. 3, it is necessary that a very large number, that is more than half, of the ions initially present in the ground state be pumped into the excitation state and then relax back to the metastable state C before such an inversion can be achieved. Succinctly stated, for population inversion, it is necessary that there be a larger number of ions in the higher energy metastable state than in the lower energy state to which the transition is to occur to produce the desired emission. Where this transition is from the metastable state directly to the ground state, which is highly populated, it is obvious that an extremely large number of ions must be pumped from the ground state A to the excitation state D. However, with a material having the energy level characteristics depicted in FIG. 4, where the fluorescent transition utilized to produce the output is from the metastable state C to the terminating state B above the ground state, much less pumping energy is required to exceed the threshold for the material and produce the desired oscillation. This is so because in the quiescent condition, that is in the absence of pumping energy, the terminating state B is essentially depopulated and, therefore, only a relatively small number of ions need be pumped to the excitation state and leak back to the metastable state C in order to achieve a population inversion or negative temperature, as defined in U.S. Patent 2,929,922 between states C and B.

As was stated above with reference to FIG. 4, the ions, once they reach the metastable state C, may undergo spontaneous emissions both to the ground state A and terminating state B. However, as the input pumping en-

ergy is increased, a condition is rapidly reached wherein there is a sufficient population inversion between the higher energy state C and lower energy state B to produce stimulated emission between these states. This stimulated emission rapidly increases the energy of the light propagated along the cavity, as depicted in FIGS. 1 and 2, and oscillations at the characteristic wavelength for this transition from state C to state B, 2.5 microns, build up in the cavity. This population inversion between states C and B is attained with a much smaller pumping energy than would be required to produce a sufficient population inversion for stimulated emission between states C and A, and being reached first as the pumping energy is built up, the transition from state C to state B is favored and causes continued stimulated emission between these states resulting in oscillation so that there are only a small number of ions which undergo the less favored transition from state C to state A. This small amount of spontaneous emission in this less favored transition from state C to state A is at the wavelength 2.2 microns.

As was pointed out above, oscillation in the cavity formed by the maser material, whose characteristics are depicted in FIGS. 4 and 5, is realized for a relatively small energy input pumping signal because of the very low population of the terminating state B, thereby requiring the pumping of only a relatively small number of ions to achieve a population inversion between state C and state B. This effect is enhanced by cooling the material to very low temperature, preferably below liquid nitrogen temperature. By this cooling, the population of ions in the terminating state B is further depleted and almost all of the ions are in the ground state A. When cooled in this manner, only a very small amount of input pumping energy is required to achieve a population inversion between the metastable state C and the terminating state B necessary for the desired stimulated emission resulting in the cavity.

The energy level diagram of FIG. 4 includes one further non-radiative transition not present in that of FIG. 3 and that is the transition designated Y_2 from the terminating state B to the ground state A. This transition occurs for those ions which have undergone a fluorescent transition from state C to state B, and it is characteristic of the preferred maser material that the rate at which these non-radiative transitions take place is greater than the rate of fluorescent transitions from metastable state C to terminating state B. This is an important feature of the material since, if the decay from state B to ground state A is slow, the population of state B is rapidly built up, thereby making it necessary, if population inversion between states B and C is to be maintained, to apply much more pumping energy. Further, even in the presence of increased pumping energy, if the decay rate from state B to state A is slow, the population at state B would build up, thereby making continuous operation of the device impossible.

Optical masers having energy characteristics such as are shown in FIGS. 4 and 5 have been fabricated with host crystals doped with a small amount of trivalent uranium. The trivalent uranium ion in the crystal lattice provides at least one strong absorption band, as is indicated in FIG. 4, at D, required if the crystal is to absorb sufficient energy from the input light to produce the desired stimulated emission. Further, the trivalent uranium provides extremely narrow fluorescent lines such as those indicated at 2.2 and 2.5 microns in FIG. 5, and these lines become even narrower at extremely low temperature. Narrow fluorescent lines are important since the narrower the line, the more favorable are the conditions for achieving monochromatic, coherent light output. Further, with the trivalent uranium ion, not too many competing fluorescent transitions are produced. In the energy level diagram of FIG. 4, the transition from metastable state C to terminating state B is the one which is utilized to produce the desired output. The only competing transition shown is that from the metastable state C to ground state A. Though crystals doped with trivalent uranium may include another energy state above state C, from which fluorescent transitions could take place, both to terminating state B and ground state A to produce two more fluorescent lines in the spectrum, not shown in FIG. 5, these competing transitions are still small in number and do not have any appreciable deleterious effect on the number of ions available for transitions from state C to state B which produce the output.

The trivalent uranium ion provides the intermediate state B between the metastable state C and ground state A and this is a characteristic of this ion. The presence of the terminating state B and the fact that the fluorescent transition which is stimulated terminates in this state rather than in ground state A, makes it possible to produce oscillation in the crystal cavity with a relatively small amount of input pumping energy. Further, since the uranium ions relax from the terminating state to the ground state at a rate faster than the rate of transitions from the metastable state to the termination state, continuous wave operation is realizable. Uranium ions also produce, as is evident from the diagram of FIG. 5, extremely strong fluorescent transitions, thereby facilitating the stimulated emission required of an optical maser.

The crystal which serves as the host lattice to be doped with the trivalent uranium should have good optical quality to thereby prevent scattering and absorption of light waves propagated along the axis of the cavity. The crystal should also be one into which the impurity ion, trivalent uranium, may be easily introduced. The host crystal should also have a high degree of symmetry and it is preferable that it be cubic and, therefore, exhibit an isotropic index of refraction. These criteria are satisfied by a number of host crystals among which may be numbered the alkaline earth fluorides, including calcium fluoride, barium fluoride and strontium fluoride. Crystals of each of these materials satisfy each of the above criteria. They have good optical quality; the divalent calcium, barium and strontium ions have a radius which is very close to that of the trivalent uranium ion, thereby allowing the latter ion to substitute easily in the crystal lattice. Crystals of these materials are cubic and, therefore, cavities such as shown in FIGS. 1 and 2, fabricated of these crystals doped with trivalent uranium have a high degree of symmetry and an isotropic index of refraction. This being the case, the direction in which the crystal is cut in forming the desired cavity is unimportant since any geometrical distortion in the material does not change the propagation characteristics as long as the reflecting surfaces 16 and 18 are parallel to each other. Thus, with these crystalline materials, even though the crystal axis is not exactly perpendicular to the reflecting surfaces, as a result of twinning or shape distortion in the crystal, the isotropic index of refraction in the cubic crystal allows for propagation without undue losses or the production of unwanted modes as could occur in an anisotropic crystal.

Therefore, though anisotropic crystals doped with trivalent uranium may be utilized in practicing the invention, cubic host crystals, such as those mentioned above, having an isotropic index of refraction, are preferred.

The energy level diagram of FIG. 4 and the spectrum diagram of FIG. 5 actually represent certain of the characteristics of a calcium fluoride crystal doped with .05% trivalent uranium. This crystal has a strong absorption band centered at .56 micron which corresponds to light in the green portion of the spectrum. This material also possesses a high degree of absorption in the blue (not shown) and varying degrees of absorption in other portions of the visible spectrum and, therefore, is capable of being easily pumped with visible light, including blue and green components. This calcium fluoride crystal

doped with .05% trivalent uranium exhibits the fluorescent lines at 2.2 and 2.5 microns, shown in FIG. 5, and two other fluorescent lines at 2.15 and 2.4 microns, resulting from the transitions from another energy level (not shown) to states A and B. However, with only these two fluorescent transitions and that from metastable state C to ground state A competing with the preferred transition from metastable state C to termination state B, by far the largest number of ions are available for the favored transition from metastable state C to terminating state B.

Barium fluoride and strontium fluoride when doped with trivalent uranium exhibit similar energy level characteristics differing in that the absorption and fluorescent bands in these crystals do not correspond exactly in wavelength to those for calcium fluoride crystals. Each of these crystals when doped with trivalent uranium exhibits a strong absorption band in the visible light portion of the spectrum, only a small number of competing fluorescent transitions, and at least one intense fluorescent transition from a metastable state to a terminating state above the ground state as indicated in FIG. 4 which can be stimulated to produce maser operation in response to a relatively small amount of input pumping energy.

FIG. 6 is a somewhat diagrammatic representation of one embodiment of an optical maser device constructed in accordance with the principles of the invention and operated at an extremely low temperature. In this figure, designations corresponding to those used in FIGS. 1 and 2 are used to identify like components. Therefore, numeral 10 designates the crystal cavity having reflecting surfaces 16 and 18. The crystal is the calcium fluoride crystal doped with trivalent uranium whose characteristics are represented in FIGS. 4 and 5 and was prepared in the following manner.

Selected and purified pieces of calcium fluoride are placed in a graphite crucible together with a measured amount of uranium metal. A small amount (about 2%) of lead is also added to the mixture. The mixture is heated slowly to a temperature above the melting points of both the calcium fluoride and the uranium metal. At this elevated temperature, the lead reacts with the oxygen present to form lead oxide which has a high vapor pressure and, is, therefore, easily pumped away. All of the lead originally added to the mixture is used up in this way so that there is not trace of lead in the end product. This occurs as the crystal is being grown in the graphite crucible and provides a highly reductive atmosphere during the growing process. The crucibles are designed to provide a crystal of calcium fluoride which is cylindrical in shape, having a radius of about ¼ inch, and a length of about 3 inches. The crystal is red in color. After the crystal is prepared in this manner, it is cut down to a diameter of about ⅜ inch and a length of about 1½ inches. The ends of the crystal are then polished to a flatness of $\frac{1}{20}$ sodium wavelengths and made parallel to within 15 seconds of an arc across the end surfaces. The cylindrical surface is left rough ground. Finally, the ends of the crystal are silvered and then covered with a protective optical coating of silicon monoxide to prevent oxidation of the silver. One of the two ends, specifically end 16, as shown in FIG. 6, is made completely opaque and the other end is silvered in such a way that it transmits 1.5% of light incident thereon. The silicon monoxide coating has a thickness, as measured, of approximately one-half wavelength at 2.5 microns.

The crystal, which forms the cavity 10 having the reflecting surfaces 16 and 18, as prepared above, is mounted as shown in FIG. 6 in a long cylindrical tube 30, which is mounted in a dewar vessel having an outer surface 36 and an inner container 32 which is about half filled with liquid helium 34. A vacuum is maintained in the space between the liquid helium container 32 and the outer surface 36. The crystal cavity 10 is mounted

with its surface 18, which is capable of transmitting 1.5% of incident light, inside the cylindrical tube 30. This tube is also evacuated. Since the tube 30 passes through the liquid helium 34 in container 32, this tube is essentially at 4.2° K., which is the boiling point for liquid helium at atmospheric pressure. The mounting for the cavity 10 in tube 30 is brass so that the crystal is at a temperature very close to liquid helium temperature.

The operation of the device is similar to the operation described with reference to FIG. 1. The pumping light input, represented by the arrows 12, is applied through a window 50 to the surface of the cylindrical cavity 10. This light is provided by a source 40, which is mounted in a light shield 42 to minimize losses. This light source is an xenon discharge lamp which is actuated under the control of a bank of condensers that are first charged and then discharged when the lamp is triggered. The output coherent light produced by the cavity 10 is, as before, represented by the arrows 14, and this light travels along the tube 30 to an output window 44 in the top of the tube and is applied to a detector 24 which, in the illustrative embodiment, includes a filter for filtering out outputs at other than the desired wavelength.

In order to provide a visual demnostration of the output of detector 24 in response to the light output from crystal 10, an oscilloscope may be connected to this detector in which case outputs as shown in FIGS. 7A, 7B and 7C are realized. FIG. 7A shows the voltage produced by the detector 24 in response to the light output from the device of FIG. 6 when the input pumping light supplied by source 40 is below the threshold intensity. FIG. 7B represents the voltage realized when the pumping light supplied by source 40 has an intensity above the threshold intensity for the device. As can be seen, the output voltage representative of the light output applied to detector 24 rises very sharply and, for the particular gain setting used, which is the same as that used for FIG. 7A, is so large as to exceed the range of the oscilloscope. It is estimated that this output has a magnitude greater than that produced by the spontaneous emission and background scattered light, as plotted in FIG. 7A, by a factor of about one thousand. FIG. 7C depicits the same output as that shown in FIG. 7B with the gain of the oscilloscope appreciably reduced. As can be seen from the right hand portion of this curve, the gain setting is such that the output, before the threshold intensity is exceeded, appears essentially as a zero output, compared with the very large output indicated after the threshold intensity has been exceeded.

The specific calcium fluoride crystal doped with .05%, described above, produces an output in the infrared region having a wavelength of 2.5 microns. Further, the output frequency shifts somewhat as the amount of doping of the host crystal is changed. Thus, for example, when the calcium fluoride crystal is doped with .1% of trivalent uranium, the infrared output has a characteristic wavelength somewhat greater than 2.5 microns. As the amount of the trivalent uranium added as an impurity is increased, the absorption of the crystalline maser material is also increased and, thus, for impurity concentrations greater than .3%, a large portion of the input energy is absorbed in the outer surface of the crystalline material. Therefore, for devices having the dimensions in the ranges indicated above, it is preferable that the amount of trivalent uranium impurity be less than .3% or that the cavity radius be decreased.

From the above description, it is apparent that, in accordance with the principles of the present invention, optical devices are provided having characteristics which have not been heretofore realizable. This is made possible by the characteristics of the trivalent uranium ion when used as a doping material. These trivalent uranium masers exhibit strong pumping bands and intense fluorescent lines. Further, they are excitable with relatively low input power by stimulating transitions to a ter-

mination state above the ground state, and are capable of either intermittent or continuous wave operation. By proper choice of material and the amount of doping, not only are outputs in the infrared realizable but at different wavelengths in the infrared. By using host crystals having cubic lattice structures, the optical properties of the devices are greatly enhanced because of the isotropic index of refraction exhibited by masers prepared in this manner.

It will, of course, be apparent to those skilled in the art that devices embodying the subject invention may be used in other applications than those illustrated in FIGS. 1 and 2. As one example, the device may be operated in such a way that one light input supplying the pumping light supplies sufficient energy to maintain the device just below its threshold and the device is triggered into oscillation by the selective application of another light source of sufficient light energy to cause the threshold to be exceeded.

While the invention has been particularly shown and described with reference to preferred embodiments thereof, it will be understood by those skilled in the art that the foregoing and other changes in form and details may be made therein without departing from the spirit and scope of the invention.

What is claimed is:

1. A maser device for producing coherent radiation comprising; means for forming a resonant structure for said coherent radiation; a body of maser material disposed within said resonant structure means; means for applying input radiation to said body for producing coherent output radiation by stimulated emission in said body; and output means for receiving said output coherent radiation from said body; said body comprising a crystal doped with trivalent uranium.

2. A maser device for producing coherent radiation comprising; means for forming a resonant structure for said coherent radiation; a body of maser material disposed within said resonant structure means for producing coherent output radiation by stimulated emission in said body; said body comprising a crystal doped with trivalent uranium in which said stimulated emission is produced by ionic transitions of said trivalent uranium between first and second energy states in said crystal both of which are above the ground energy state of said trivalent uranium in said crystal; means for exciting said trivalent uranium so as to produce a sufficient population inversion between said first and second energy states to provide stimulated emission of said coherent radiation in said crystal, and means for extracting said coherent radiation from said resonant structure means.

3. A maser device for producing coherent radiation comprising; means for forming a resonant structure for said coherent radiation; a body doped with trivalent uranium disposed within said resonant structure means; means for applying input radiation to said body for producing monochromatic, coherent output radiation from said body by stimulated emission in said body of ionic transitions of said trivalent uranium from a first energy state to a second energy state in said body, both of which states are above the ground energy state for said body; and output means for receiving said output coherent radiation from said body.

4. The device of claim 3 wherein said crystal is cubic.

5. The device of claim 4 wherein said crystal is an alkaline earth fluoride crystal.

6. The device of claim 5 wherein said crystal is barium fluoride.

7. The device of claim 5 wherein said crystal is strontium fluoride.

8. The device of claim 5 wherein said crystal is calcium fluoride, and said output coherent light has a wavelength in the infrared portion of the spectrum.

9. The device of claim 8 wherein said crystal is calcium fluoride and is doped with about .05% of trivalent uranium.

10. The device of claim 8 wherein said crystal is calcium fluoride and is doped with about .1% of trivalent uranium.

11. In an optical maser device for continuously producing coherent output radiation by continuous stimulated emission in a crystal maser material; means for forming a resonant structure for said coherent radiation embracing said crystal maser material; means maintaining said crystal at a temperature below that of liquid nitrogen; said crystal being doped with trivalent uranium to exhibit a strong absorption band, a ground energy state, and first and second other energy states both of which are above said ground energy state; said stimulated emission being produced by fluorescent ionic transitions of said trivalent uranium from said first energy state to said second energy state; said first energy state being populated by applying energy to pump trivalent uranium ions from said ground state to said absorption band which ions then undergo a non-radiative transition to said first state; said ions undergoing non-radiative transitions from said second energy state to said ground state at a faster rate than said fluorescent transitions from said first energy state to said second energy state; whereby continuous stimulated emission is produced in said body by the continuous application of input energy to said body, and means for extracting said coherent radiation from said crystal maser material.

12. A maser device for producing coherent radiation comprising; means for forming a resonator for said coherent rediation; a crystal doped with trivalent uranium disposed within said resonator means; means for producing emission from said doped crystal by stimulating fluorescent ionic transitions of said trivalent uranium between different energy states in said crystal; and output means responsive to said emission.

13. A maser device for producing coherent radiation comprising; means for forming a resonator for said coherent radiation; a calcium fluoride crystal doped with a small amount of trivalent uranium disposed within said resonator means; means for producing infrared emission from said doped crystal by stimulating fluorescent ionic transitions of said trivalent uranium between different energy states in said crystal; and output means responsive to said infrared emission.

14. A maser device for producing coherent radiation comprising; means forming a resonator for said coherent radiation; a crystal having an isotropic index of refraction doped with trivalent uranium disposed within said resonator means; means for producing emission from said doped crystal by stimulating fluorescent ionic transitions of said trivalent uranium between different energy states in said crystal; and output means responsive to said emission.

15. An optical maser device comprising; a crystal doped with trivalent uranium whereby said doped crystal exhibits strong absorption bands in the visible portion of the spectrum and a fluorescent band in the infrared portion of the spectrum; said fluorescent band being produced by ionic transitions of the trivalent uranium from a first energy state to a second energy state both of which are above the ground energy state for said trivalent uranium in said crystal; means forming a resonator at said fluorescent band containing said doped crystal; means for cooling said crystal to thereby narrow said fluorescent band and decrease the population of said second energy state relative to said ground state; input means for producing stimulated emission in said crystal by causing stimulating ionic transitions of said trivalent uranium from said first energy state to said second energy state; and output means responsive to said emission.

16. The device of claim 15 wherein said crystal is in the form of a rod having parallel ends and wherein said resonator means includes a pair of mutually parallel plates both of which are at least partially reflecting.

17. The device of claim 15 wherein said crystal is cubic.

18. The device of claim 17 wherein said crystal is an alkaline earth crystal.

19. The device of claim 18 wherein said crystal is a calcium fluoride crystal doped with trivalent uranium and said emission produced by said stimulated transitions is in the infrared.

20. A solid state maser for producing coherent radiation of a given optical frequency in the electromagnetic wave spectrum comprising means forming an optical resonator for said coherent radiation, a negative temperature medium disposed within said resonator means and having a plurality of individual ions each characterized by a ground energy level and at least three distinct energy levels above said ground level, two of said three energy levels having a separation corresponding to said given optical frequency and disposed between the third of said three energy levels and the ground level, means for exciting said ions to the third of said three energy levels so as to produce a negative temperature with respect to said two energy levels causing stimulated emission of said coherent radiation and means for extracting said generated coherent radiation from a surface of said medium.

21. A maser device for producing coherent radiation of a given optical frequency in the electromagnetic wave spectrum comprising a solid state host material including ions each of which are characterized by a given absorption band of frequencies and by a ground energy level and a pair of energy levels above said ground level between which stimulated emission is produced at said given optical frequency, means for applying pumping radiations within said absorption band of frequencies to said ions so as to produce a population inversion between said pair of energy levels to cause stimulated emission of said coherent radiation, means for forming a reasonant structure for said coherent radiation and means for emitting said coherent radiation from said resonant structure means.

22. A maser device for producing coherent radiation of a given optical frequency in the electromagnetic wave spectrum comprising means forming an optical resonator for said coherent radiation, a host medium disposed within said resonator means and having ions each characterized by a ground energy level and first, second and third energy levels each above said ground level, an ionic transition between said first and second energy levels being instrumental in producing the coherent radiation by stimulated emission, means for exciting said ions to the third of said three energy levels so as to create a population inversion with respect to said first and second energy levels producing stimulated emission of coherent radiation within said medium and means for extracting a portion of said coherent radiation from said medium.

23. A device as set forth in claim 22 wherein ionic transitions from said third energy level to said first energy level and from said second energy level to said ground energy level are non-radiative transitions.

24. A maser device for producing coherent radiation of a given optical frequency comprising a medium including trivalent uranium ions, means for exciting said ions to create a population inversion producing stimulated emission of coherent radiation within said medium, means for forming a resonant structure for said coherent radiation and means for extracting said coherent radiation from said resonant structure means.

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Dec. 14, 1965 J. L. HYDE 3,223,842
DIGITAL MEASURING APPARATUS UTILIZING
A RADIOACTIVE SOURCE AND DETECTOR
Filed March 15, 1962

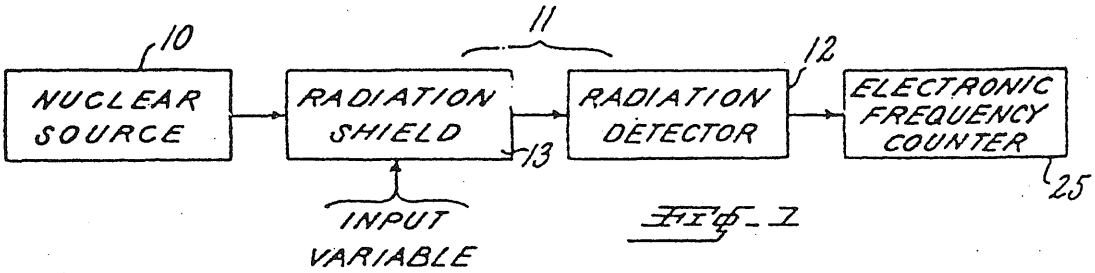


Fig. 1

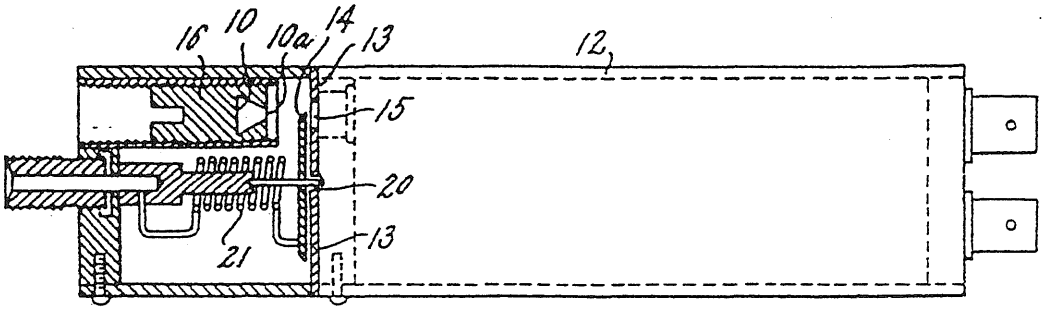


Fig. 2

Fig. 3a

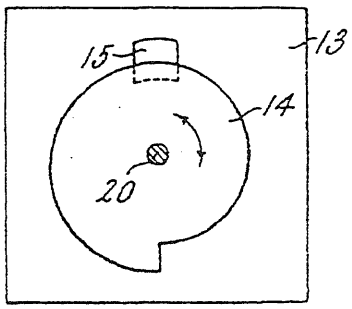
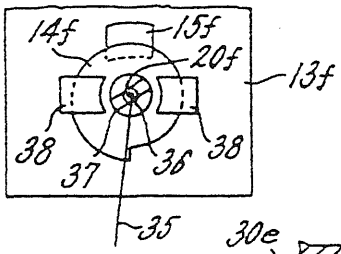


Fig. 3f



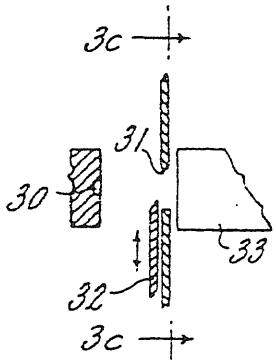


Fig. 3b

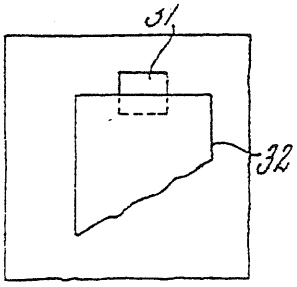


Fig. 3c

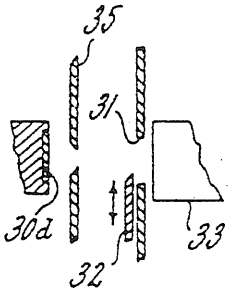


Fig. 3d

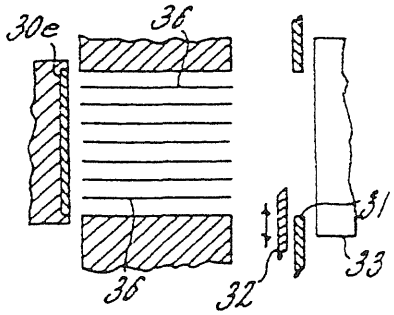


Fig. 3e

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DIGITAL MEASURING APPARATUS UTILIZING A RADIOACTIVE SOURCE AND DETECTOR

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Filed Mar. 15, 1962, Ser. No. 180,6[illegible]0

7 Claims. (Cl. 250—83.3)

This invention relates to measuring apparatus, and more particularly, to measuring apparatus for developing an output signal representing a physical variable such as pressure, temperature, or acceleration which may be sensed through a mechanical displacement.

Measuring apparatus heretofore proposed has, in general, been subject to various inaccuracies or limitations. For example, electronic apparatus is generally subject to changes in circuit parameters due to variations in operating conditions resulting in output signal inaccuracies or drift.

Prior measuring apparatus utilizing nuclear or radioactive energy sources has been subject to the limitation that the apparatus develops analog output signals subject to inaccuracies due to electronic circuit instabilities effecting the magnitude and thus the accuracy of the output signals. Moreover, output signals which vary linearly with or in proportion to an input variable have not ordinarily been provided by energy transducers utilizing a radioactive energy source.

Further, prior analog-to-frequency signal converters usually utilize voltage-controlled oscillators which are subject to instabilities due to variations of operating conditions.

It is an object of the invention, therefore, to provide a new and improved measuring apparatus.

It is another object of the invention to provide a new measuring apparatus having improved accuracy.

It is another object of the invention to provide a new and improved digital measuring apparatus providing digital signals translatable entirely in pulse-coded digital form.

It is another object of the invention to provide a stable digital measuring apparatus.

It is another object of the invention to provide a new and improved digital energy transducer for measuring apparatus.

It is another object of the invention to provide a new and improved stable analog-to-frequency signal converter.

In accordance with the invention, digital measuring apparatus comprises a radioactive energy source and means controlled by a variable to be measured for providing pulses representing the radiation particles and having a pulse rate which varies in accordance with the variable to be measured. The apparatus also includes terminal utilizing means responsive to the electrical pulses for developing digital output signals representing the variable.

For a better understanding of the present invention, together with other and further objects thereof, reference is made to the following description taken in connection with the accompanying drawings, and its scope will be pointed out in the appended claims.

Referring now to the drawings, FIG. 1 is a schematic block diagram of a digital measuring apparatus constructed in accordance with the invention;

FIG. 2 is a view in section, partly diagrammatic, of a portion of the FIG. 1 apparatus; and

FIGS. 3*a* to 3*f*, inclusive, are diagrammatic representations of various transducers constructed in accordance with the invention.

Referring now more particularly to FIG. 1 of the drawings, measuring apparatus constructed in accordance with the invention comprises a nuclear or radioactive energy source 10 which may emit, for example, alpha, or beta

particles or gamma rays. Typically the nuclear source may be strontium 90 which emits beta particles or polonium 210 which emits alpha particles. The source 10 preferably is a point source which is collimated through collimator opening 10*a* to produce a substantially parallel beam of particles. A radioactive source having a magnitude of the order of 10 to 1000 microcuries is suitable for many applications.

The particles emitted by the source 10 are directed to means 11 controlled by a variable to be measured for providing electrical pulses representing the radiation particles and generating a pulse rate which varies in accordance with the variable to be measured. More particularly, the means 11 comprises a radiation shield having a displaceable member controlled in position by a variable to be measured for controlling the rate of radiation particles transmitted through the shield, as will be more fully described subsequently. The means 11 also comprises a radiation detector 12 providing individual electrical pulses representative of the individual radiation particles transmitted through the shield.

Referring more particularly to FIG. 2, there is represented a pressure-responsive transducer in which the radiation shield comprises, for example, a dense metal shield 13 having a displaceable member 14 controlling the width of an aperture 15 for transmitting particles emitted by a source 10. The displaceable member is in the form of a rotatable spiral cam shutter 14 positioned between the aperture 15 and the source 10, as represented in FIG. 3*a*. Referring again to FIG. 3, rotation of the shutter 14 controls the rate of radiation particles transmitted through the aperture. The source 10 may be enclosed in an adjustably positioned capsule 16.

The cam shutter 14 is mounted on a rotatable central shaft 20. The periphery of the cam shutter 14 is attached to and is rotatable under the control of a helical Bourdon tube such as manufactured by Glassco Instrument Co., Pasadena, California or other Bourdon tube of conventional construction. The Bourdon tube deforms and rotates the shutter 14 in accordance with pressure applied to the Bourdon tube through aperture 15.

The radiation detector 12 may be a Geiger tube of conventional construction positioned in line with the aperture 15 and source 10 to develop electrical output pulses individually representative of the individual radiation particles transmitted through the aperture. The Geiger tube preferably is of the thin window type having a window thickness of 1 to 3 milligrams per square centimeter. Any suitable radiation detector, such as a semiconductor particle detector, may be used in lieu of a Geiger tube.

Referring again to FIG. 1, there is coupled to the radiation detector 12 terminal utilizing means responsive to the individual electrical pulses for developing output signals comprising a digital representation of the rate of individual radiation particles transmitted through the shield and thus comprising a digital representation of the variable. This terminal utilizing means may be a digital frequency counter or pulse counter 25 of a conventional type providing a digital count over a preset time base of the pulses applied thereto and a digital signal output or digital readout. Such a digital frequency counter may be of a type manufactured by Beckman Instruments, Inc., Richmond, California. The digital readout or signal output may be for example, visual digital signals or electrical or magnetic pulse-coded signals, such as binary pulse-coded signals. The terminal utilizing means may, for example, also include a magnetic tape or a digital telemetering output circuit. The terminal utilizing means develops output signals for the measuring of apparatus and is not utilized merely to convert the pulses internally within the apparatus to an analog signal.

Other transducers similar to the FIG. 1 transducer and constructed in accordance with the present invention are represented diagrammatically in FIGS. 3*b* to 3*c*. Referring to FIGS. 3*b* and 3*c*, a radioactive point source 30 may be utilized in proximity to a shield having an aperture 31 which may be adjusted by a linearly displaceable shutter 32 for determining the rate of particles which strike radiation detector 33. The aperture 31 effectively acts as a collimator to pass substantially parallel rays of the beam of particles toward the detector 33. The dimensions of the aperture, which may be rectangular, and the shape of the shutter, which may have a straight leading edge, preferably are so determined that the area of the aperture is adjusted linearly with respect to variations of the variable to be measured. Thus, the rate of radioactive particles transmitted through the aperture preferably varies linearly with displacements of the shutter. For some applications it may be desirable that the rate of particles transmitted through the aperture varies as a nonlinear function of displacement of the shutter and the dimensions of the aperture and the shape of the shutter may be designed accordingly.

As represented in FIG. 3*d*, a source 30*d* other than a point source, in conjunction with a collimator 35 having an aperture of small dimensions may be utilized to provide a beam of particles having substantially parallel rays. Another form of collimator is represented in FIG. 3*e* comprising a series of substantially parallel plates 36 which are opaque to radiation and are effective to cause the beam to have substantially plane-parallel rays, that is rays lying substantially entirely in planes perpendicular to the plane of the shutter and parallel to the leading edge of the shutter. At least such substantial plane parallelism of rays is necessary in order to provide a particle rate through the aperture varying linearly with variations of the input variable. Alternatively, a parallel bundle of thin-walled opaque tubes can be utilized to provide a beam which has substantially parallel rays in three dimensions. The radiation flux may be defined as the number of particles per second passing through an area of a square centimeter. Thus, linearity of the particle rate through the aperture, and thus of the final digital representation, with variations of the input variable can be obtained when the flux gradient through the aperture is substantially zero in the direction of motion of the shutter.

FIG. 3*f* represents a digital transducer for an analog-to-frequency signal converted. The transducer includes a moving coil galvanometer having input leads 35 electrically connected through conductive springs 36 (only one of which is shown in the drawing) to a rotatable winding 37 mounted on a rotatable shaft 20*f* within a suitable magnet assembly 38 for controlling the position of a cam shutter 14*f* across an aperture 15*f* in ressponse to an analog electrical input signal. Rotation of the shutter 14*f* controls the rate of radiation particles transmitted from a suitable nuclear source through the aperture to a radiation detector and frequency counter, as represented in FIG. 1.

From the foregoing description it will be apparent that measuring apparatus constructed in accordance with the invention has the advantage that the information representing the variable to be measured can be translated entirely in digital form, thereby providing high output signal accuracy with minimum equipment. The apparatus includes a digital transducer of an extremely stable nature. Moreover, the transducer is capable of providing an output signal which varies linearly with the variations of the input variable.

While there have been described what are at present believed to be the preferred embodiments of this invention, it will be obvious to those skilled in the art that various changes and modifications may be made therein without departing from the invention, and it is, therefore,

aimed to cover all such changes and modif ations as fall within the true spirit and scope of the invention.

Having thus described my invention, what I claim and desire to protect by Letters Patent is:

1. Digital measuring apparatus comprising: a radioactive particle source; a radiation shield having an effective aperture area and having a displaceable shutter in proximity to said aperture area and controlled in position by a variable to be measured for controlling the rate of radiation particles transmitted through said shield; the flux gradient of the particles emitted by said source being substantially zero through said effective aperture area in the direction of motion of said shutter; a radiation detector providing individual electrical pulses representative of the individual radiation particles transmitted through said shield; and terminal utilizing means responsive to said individual electrical pulses for developing output signals comprising a digital representation of the rate of said individual radiation particles transmitted through said shield and thus comprising a digital representaton of said variable.

2. Digital measuring apparatus comprising: a radioactive energy source emitting radiation particles in a beam having substantially parallel rays; a radiation shield having a displaceable shutter controlled in position by a variable to be measured and having in proximity to said shutter an effective aperture area which is linearly adjustable with displacement of said displaceable shutter for controlling the rate of radiation particles transmitted through said shield; a radiation detector providing individual electrical pulses representative of the individual radation particles transmitted through said shield; and terminal utilizing means responsive to said individual electrical pulses for developing output signals comprising a digital representation of the rate of said individual radiation particles transmitted through said shield and thus comprising a digital representation varying linearly with said variable.

3. Digital measuring apparatus comprising: a radioactive particle source; a radiation shield having an effective aperture area and having a displaceable shutter in proximity to said effective aperture area and controlled in position by a variable to be measured for controlling the rate of radiation particles transmitted through said shield; the flux gradient of the particles emitted by said source being substantially zero through said effective aperture area in the direction of motion of said shutter; a radiation detector providing individual electrical pulses representative of the individual radiation particles transmitted through said shield; and a digital frequency counter responsive to said individual electrical pulses for developing output signals comprising a digital representation of the rate of said individual radiation particles transmitted through said shield and thus comprising a digital representation of said variable.

4. A digital energy transducer for measuring apparatus comprising: a radioactive particle source; a radiation shield having an effective aperture area and having a displaceable shutter in proximity to said effective aperture area and controlled in position by a variable to be measured, said effective aperture area being adjustable with displacement of said shutter for controlling the rate of radiation particles transmitted through said shield; the flux gradient of the particles emitted by said source being substantially zero through said effective aperture area in the direction of motion of said shutter; and a radiation detector providing individual electrical pulses representative of the individual radiation particles transmitted through said shield.

5. A digital energy transducer for measuring apparatus comprising: a radioactive particle source; a radiation shield having an effective aperture area and having a displaceable shutter in proximity to said effective aperture area and controlled in position by a variable to be measured, the flux gradient of the particles emitted by said

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source being substantially zero through said effective aperture area in the direction of motion of said shutter, said effective aperture area being linearly adjustable with displacement of said shutter for controlling the rate of radiation particles transmitted through said shield; and a radiation detector providing individual electrical pulses representative of the individual radiation particles transmitted through said shield.

6. A digital energy transducer for an analog-to-frequency system converter comprising: means for supplying an analog electrical input signal; a galvanometer including a moving coil positioned in response to said input signal; a radioactive particle source; a radiation shield having a displaceable member controlled in position by said moving coil and having an effective aperture area adjustable with displacement of said displaceable member for controlling the rate of radiation particles transmitted through said shield, the flux gradient of the particles emitted by said source being substantially zero through said effective aperture area in the direction of motion of said shutter; and a radiation detector providing individual electrical pulses representative of the individual radiation particles transmitted through said shield.

7. A digital energy transducer for measuring apparatus

comprising: a radioactive particle source; a radiation shield having an effective aperture area and having a rotatable shutter in proximity to said effective aperture area and controlled in position by a variable to be measured, said effective aperture area being adjustable with rotation of said shutter for controlling the rate of radiation particles transmitted through said shield; the flux gradient of the particle emitted by said source being substantially zero through said effective aperture area in the direction of motion of said shutter; and a radiation detector providing individual electrical pulses representative of the individual radiation particles transmitted through said shield.

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May 31, 1966 R. E. BLACK 3,254,211

RADIOACTIVE RADIATION TRANSDUCER DEVICE FOR MEASURING VARIABLE CONDITIONS

Filed Dec. 11, 1961

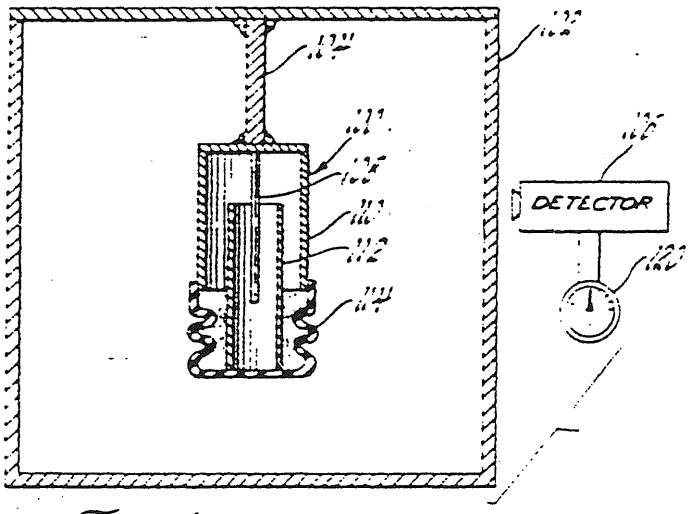

Fig. 1

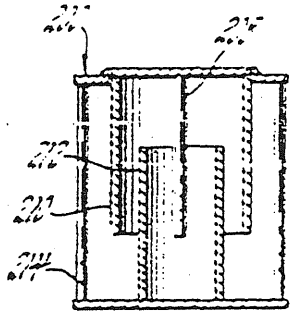

Fig. 2

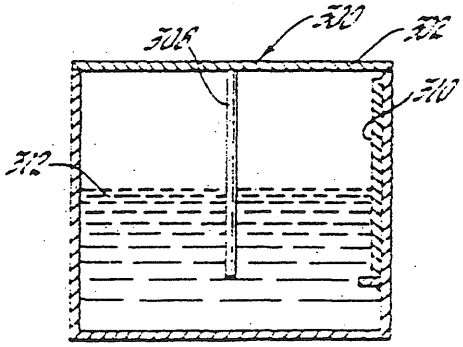

Fig. 3

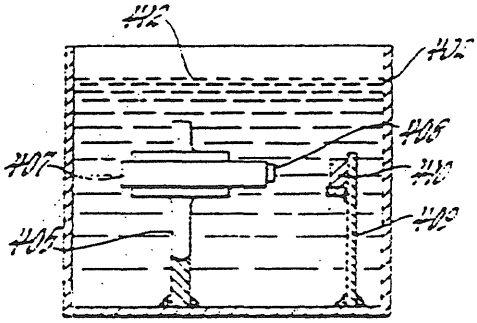

Fig. 4

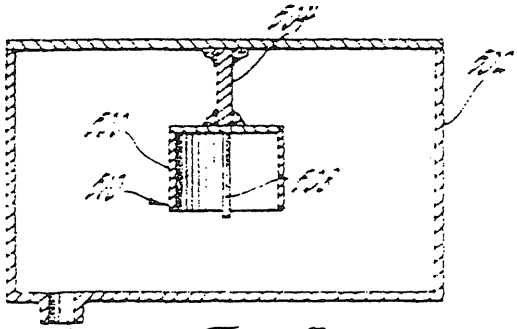

Fig. 5

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Patented May 31, 1966

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RADIOACTIVE RADIATION TRANSDUCER DEVICE FOR MEASURING VARIABLE CONDITIONS

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Filed Dec. 11, 1961, Ser. No. 158,388
14 Claims. (Cl. 250—43.5)

This invention relates to measuring instruments and more particularly to improvements in measuring instruments comprising a radiation transducer device.

In previously known measuring instruments it has not been possible to make a measurement of a condition within a closed assembly such as a transmission housing, for example, and to send the information outside the assembly without the use of electrical or mechanical connections. Frequently it is undesirable to make such connections because of the expense involved, because of the deleterious effect of the connections on the assembly, or because the mere existence of such connections may tend to change the very condition which is to be measured.

Accordingly, it is an object of this invention to provide a method and apparatus for making the measurement of a desired condition and transmitting the information thus obtained to a location remote from the measuring device without the use of electrical or mechanical connections.

This invention is carried out by providing a transducer assembly comprising a beta particle source, a target spaced from said source for producing X-rays upon being bombarded by the particles from said source, and some means responsive to the condition to be measured for modulating the beta particles to thereby modulate the intensity of X-rays produced. An X-ray detector is located remotely from the target. Further, the invention contemplates that the target and the detector may be separated by a mass of material which can be penetrated by the X-rays.

The above and other advantages of the invention will be made more apparent from the following specification taken in conjunction with the accompanying drawings wherein like reference numerals refer to like parts, and wherein:

FIGURE 1 is a cross-sectional view of one embodiment of the invention wherein a pressure transducer is located within a closed container and an X-ray detector is located outside the container;

FIGURE 2 shows a transducer responsive to temperature according to another embodiment of the invention;

FIGURE 3 shows a transducer responsive to liquid level according to another embodiment of the invention;

FIGURE 4 is a sensing and modulation unit responsive to displacement of a mechanical element according to another embodiment of the invention; and

FIGURE 5 is a transducer responsive to gas density according to another embodiment of the invention.

FIGURE 1 of the drawings illustrates a complete measuring unit including a transducer means within a completely enclosed housing and a detector outside the housing. The remaining figures illustrate transducer units without a detector. It is intended that each of these units be used with a detector in a complete system such as that of FIGURE 1.

It has previously been known to use radiation from radioisotopes for measuring instrumentation wherein a radiation source is spaced from a radiation detector and the mass of some material existing in the space between the source and detector is measured by counting the radiation particles or photons reaching the detector and calibrating the detector output in terms of the mass, size, or density of the material. The percentage of radiation transmitted from the source to the detector will depend upon the radiation absorbing characteristics of the material and the amount of the material separating the source from the detector. However, this technique has severe limitations; for example, if an alpha or beta source is used the radiation will be easily modulated due to its poor penetration characteristics, but the detector must be placed very close to the source in order to detect the radiation. If the detector is far away from the source or separated from the source by the wall of a housing, for example, then the alpha or beta radiation will be almost completely absorbed before it reaches the detector. This difficulty can be overcome by the use of a gamma source since gamma radiation will travel long distances through air and even through solid objects without being greatly absorbed due to its good penetration characteristics. However, it is extremely difficult to modulate the gamma radiation by the intervening mass of material because of its good penetration characteristics.

The present invention takes advantage of the inherent penetration characteristics of the various types of radiation by using a beta particle source, modulating the radiation therefrom, utilizing the modulated beta radiation to produce X-rays, and then measuring the highly penetrating X-rays with a detector. This enables the detector to be placed remotely from the source and even permits the source and detector to be located on opposite sides of a wall which would be substantially impervious to beta radiation. It has been found that for the best results, only the characteristic X-rays should be measured; that is, those X-rays which have an energy characteristic of the atomic number of the target material.

Referring now to FIGURE 1, a pressure transducer 100 is located within a completely enclosed housing 102 and is supported therefrom by a member 104. A detector 106 is placed outside the housing 102 in a position opposite the transducer 100. The transducer comprises an elongated beta source 108 carried by the support member 104 and a cylindrical target member 110, also carried by support member 104 and arranged coaxially with the beta source 108. A cylindrical beta particle shield 112 is coaxially disposed between the beta source 108 and 110 and is arranged for axial movement. The shield 112 is suspended from a target 110 by a bellows 114 to form an airtight compartment within the transducer 100. As the pressure within the housing varies, the bellows will be compressed or elongated and the shield 112 will move axially between the beta source 108 and the target 110. The beta source 108 is preferably strontium 90 deposited on a graphite core. The target is made of tungsten or other high atomic number elements such as uranium, lead, or gold and the shield is composed of aluminum, but other low atomic elements including beryllium, carbon, and silicon could be substituted for aluminum.

In operation, when the pressure within the housing 102 is low, the bellows will expand to withdraw the shield 112 from shielding position. Beta particles emanating from the source 108 will impinge on the target 110 to produce characteristic X-rays which are more penetrating than the beta radiation. The X-rays will pass through the walls of the housing 102 and will be measured by the detector 106 which is connected by suitable circuitry to a meter 120 which is calibrated in terms of pressure. If the pressure within the housing 102 increases, then the bellows 114 will tend to collapse and the shield 112 will move upwardly into the region between the source 108 and target 110 thereby preventing a portion of the beta radiation from reaching the target 110 and accordingly decreasing the intensity of the characteristic X-rays produced to change the reading of the meter 120. The pressure within the housing 102 determines the amount of beta radiation which reaches the target 110 and thereby continually modulates the characteristic X-ray production.

The transducer 200 shown in FIGURE 2 is intended for thermometry applications and structurally is somewhat similar to transducer 100. It includes a beta source 208, a coaxial cylindrical target 210, a cylindrical coaxial beta shield 212, and a pair of heat expansible rods 214 composed of aluminum interconnecting the shield 212 and the target 210. The heat expansible elements 214 must have different thermal coefficients of expansion than that of the other materials in the transducer so that as the temperature of the transducer environment changes, the shield 212 will move up or down to modulate the beta radiation transmission and hence modulate the characteristic X-ray production. A detector, not shown, remote from the transducer 200 would be calibrated in terms of temperature. The materials used in the transducer 200 are similar to those in the transducer 100 except that the shield 212 should preferably be made of graphite.

FIGURE 3 illustrates a transducer 300 for measuring liquid level within a container 302. The transducer comprises an elongated beta source 308 extending vertically from the top of the container and supported thereby and a coextensive target member 310 mounted on one wall of the container 302 and parallel to the beta source 308. In this transducer the shield or modulator is the liquid 312, the level of which is to be measured. It is obvious that the liquid level will determine the amount of beta radiation reaching the target 310 and accordingly will modulate the production of characteristic X-rays at the target. As in the previous systems a detector, not shown, outside the container 302 is used to provide an indication of the amount of characteristic X-ray production and hence of the liquid level.

A displacement transducer is illustrated in FIGURE 4 and comprises a container 402 containing fluid 412. Immersed in the fluid is a stationary support 409 which holds a body of target element 410 and a further support 405 which carries a movable element 407 having a beta emitter 408 secured to one end thereof. The element 407 is suitably connected to any element, not shown, whose displacement is to be measured. If the beta source 408 is moved toward the stationary target 410, then the amount of fluid 412 between the source and target is diminished, thereby changing the amount of beta transmission to the target and hence the amount of characteristic X-rays produced for detection at a location outside of the container 402. Experiments have indicated that where the source 408 comprised a pellet of 0.04 millicurie of phosphorous-32, the target was gold and the fluid bath 412 was glycerin, very good results were obtained by using a detector comprising a scintillating crystal and photomultiplier feeding a spectrometer adjusted to detect only the characteristic gold X-rays of 68.8 kev. energy. Decreasing the source to target distance from 0.08 inch to 0.02 inch resulted in doubling the net count rate. The change in count rate was fairly linear throughout that range.

A transducer for measuring the density of a gas is shown in FIGURE 5. The transducer 510 consists of a beta radiation source 508 and a coaxial target 500, both attached by means of a supporting member 504 to a gas container 502. In this transducer the shield or modulator is gas within the container. As more gas is placed inside the container through port 514, the density will increase. As the density increases, more beta radiation from the source 508 will be absorbed by the gas. Consequently, less beta radiation will strike the target 500 and the production of characteristic X-rays will be reduced.

The transducer could be attached to the exterior of a vehicle to measure the density of gas around the vehicle. A suitable detector would then be placed inside the vehicle in this application.

It will thus be seen that this invention provides a convenient method of sensing a condition at one location and transmitting the information to a remote location without the use of electrical or mechanical connections. The

invention may be applied to many types of measuring instruments and, in fact, may be used to measure any quantity which can be made to result in mechanical motion of one part with respect to another, and it is especially useful in measuring quantities in inaccessible locations.

The embodiments of the invention disclosed herein are for illustrative purposes only and the scope of the invention is intended to be limited only by the following claims:

1. A radiation transducer for a measuring instrument comprising a beta particle source, a target spaced from said source for producing X-rays upon bombardment by beta particles from said source, means controlled by the condition to be measured for modulating the beta particles to modulate the production of X-rays, and an X-ray detector for measuring the X-ray intensity whereby the detector output is a function of the condition to be measured.

2. A radiation transducer for a measuring instrument comprising a beta particle source, a target spaced from said source for producing X-rays upon bombardment by beta particles from said source, shield means between said source and target for modulating the beta particles in accordance with the condition being measured to modulate effectively the production of X-rays, and an X-ray detector for measuring the X-ray intensity whereby the detector output is a function of the condition being measured.

3. A radiation transducer for a measuring instrument comprising a beta particle source, a target spaced from said source for producing X-rays upon bombardment by beta particles from said source, beta absorbing means between the source and target, and means responsive to the condition being measured for varying the beta absorbing means for modulating the beta particles to modulate the production of X-rays, and an X-ray detector for measuring the X-ray intensity whereby the detector output is a function of the condition being measured.

4. A radiation transducer for a measuring instrument within a housing comprising a beta particle source within the housing, a target within the housing spaced from said source for producing X-rays upon bombardment by beta particles, modulating means controlled by a condition to be measured for modulating the beta particles to thereby modulate the production of X-rays, and an X-ray detector outside the housing for measuring the intensity of X-rays passing through the housing whereby the detector output is a function of the condition.

5. A radiation transducer for a measuring instrument within a housing comprising a beta particle source within the housing, a target within the housing spaced from said source for producing X-rays upon bombardment by beta particles, beta shielding material between the source and target, the effectiveness of said material being controlled by a condition to be measured for modulating the beta particles to thereby modulate the production of X-rays, and an X-ray detector outside the housing for measuring the intensity of X-rays passing through the housing whereby the detector output is a function of the condition.

6. A radiation transducer for a measuring instrument within a housing comprising a beta particle source within the housing, a target within the housing spaced from said source for producing X-rays upon bombardment by beta particles, space between said source and target, a homogenous beta absorbing material filling said space, means for varying the spacing between said source and target thereby varying the amount of beta absorbing material between said source and target for modulating the beta particles to thereby modulate the production of X-rays, and an X-ray detector outside the housing for measuring the intensity of X-rays passing through the housing whereby the detector output is a function of the spacing between the source and target.

7. A radiation transducer for a measuring instrument comprising a beta particle source, a target spaced from said source for producing X-rays which have an energy

characteristic of the atomic number of the target upon bombardment by beta particles from said source, means controlled by the condition being measured for modulating the beta particles to modulate effectively the production of characteristic X-rays, and an X-ray detector for measuring the intensity of the characteristic X-rays whereby the detector output is a function of the condition being measured.

8. A method of measuring a condition comprising bombarding a target with beta particles to produce X-rays, modulating the beta particles as a function of the condition, and measuring the X-rays produced by the modulated beta particles whereby the intensity of the X-rays is a function of the condition being measured.

9. A method of measuring a condition comprising bombarding a target with beta particles to produce characteristic X-rays, modulating the beta particles as a function of the condition, and measuring the intensity of the characteristic X-rays produced by the modulated beta particles whereby the intensity of the X-rays is a function of the condition being measured.

10. A method of measuring a condition existing within a housing comprising bombarding a target within the housing with beta particles to produce X-rays, modulating the beta particles as a function of the condition, passing the X-rays through the housing, and measuring the intensity of the X-rays transmitted through the housing whereby the intensity of the X-rays is a function of the condition being measured.

11. A method of measuring a condition existing within a housing comprising bombarding a target within the housing with beta particles to produce X-rays, partially shielding the beta particles from the target, varying the effective shielding to modulate the beta particles as a function of the condition, passing the X-rays through the housing, and measuring the intensity of the X-rays transmitted through the housing whereby the intensity of the X-rays is a function of the condition being measured.

12. A method of measuring the displacement of an element comprising bombarding a target with beta particles

to produce X-rays, modulating the beta particles as a function of the displacement, and measuring the intensity of the X-rays produced whereby the intensity of the X-rays is a function of the displacement.

13. A method of measuring the displacement of an element within a housing comprising bombarding a target within said housing with beta particles to produce characteristic X-rays, partially shielding the target with beta absorbing material, displacing the beta absorbing material as a function of the displacement of the element, passing the characteristic X-rays through the housing, and measuring the characteristic X-rays transmitted through the housing whereby the intensity of the X-rays is a function of the displacement.

14. A method of measuring density of a gas comprising passing beta particles through the gas, bombarding a target with the beta particles transmitted through the gas to produce X-rays, and measuring the intensity of the X-rays produced whereby the intensity of the X-rays is a function of the gas density.

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May 31, 1966 R. J. FANNING ETAL 3,254,212

APPARATUS FOR DETERMINING THE CONCENTRATION OF ALUMINUM IN HYDROCARBON STREAMS BY THE USE OF K-CAPTURE RADIOACTIVITY

Filed Jan. 12, 1962 4 Sheets-Sheet 1

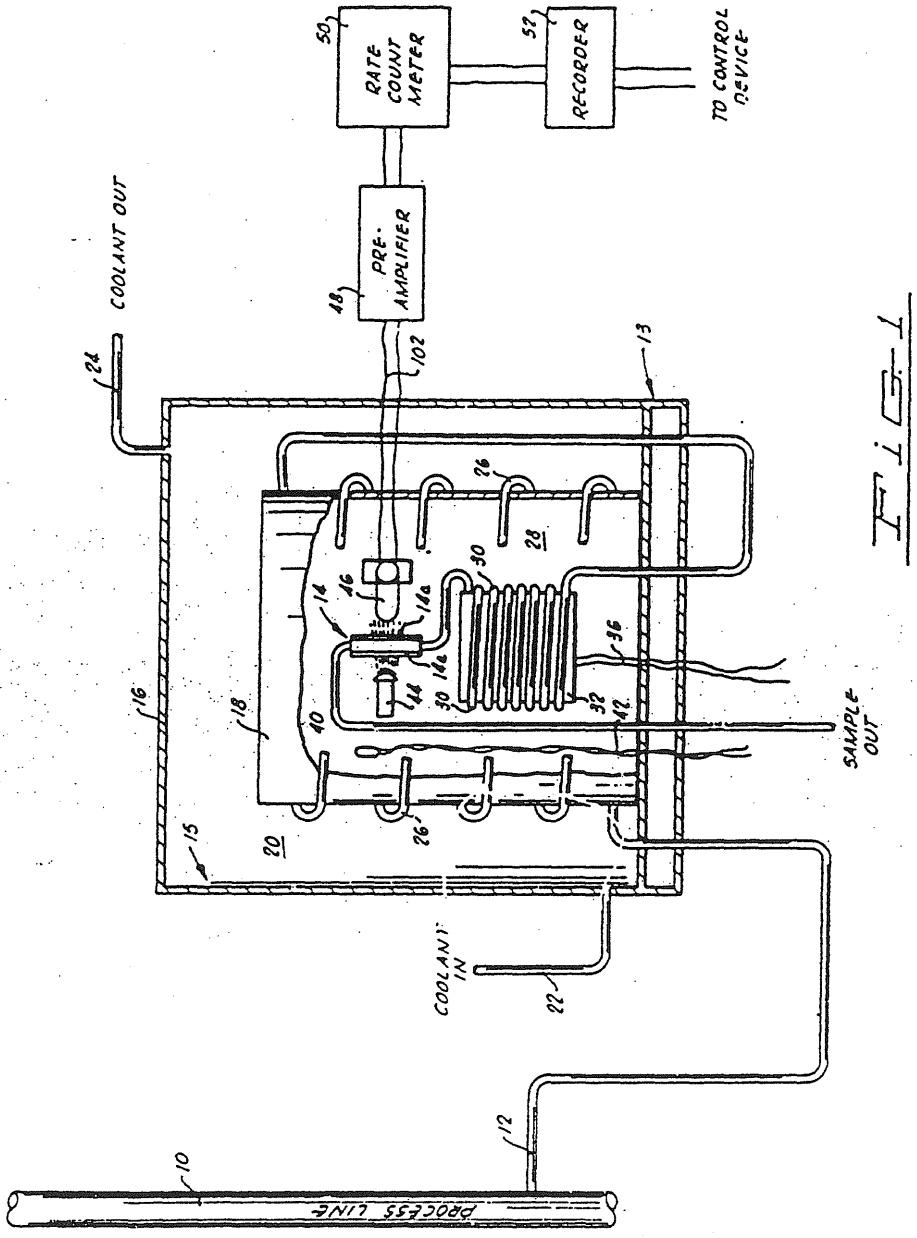

FIG. 1

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Filed Jan. 12, 1962 4 Sheets-Sheet 2

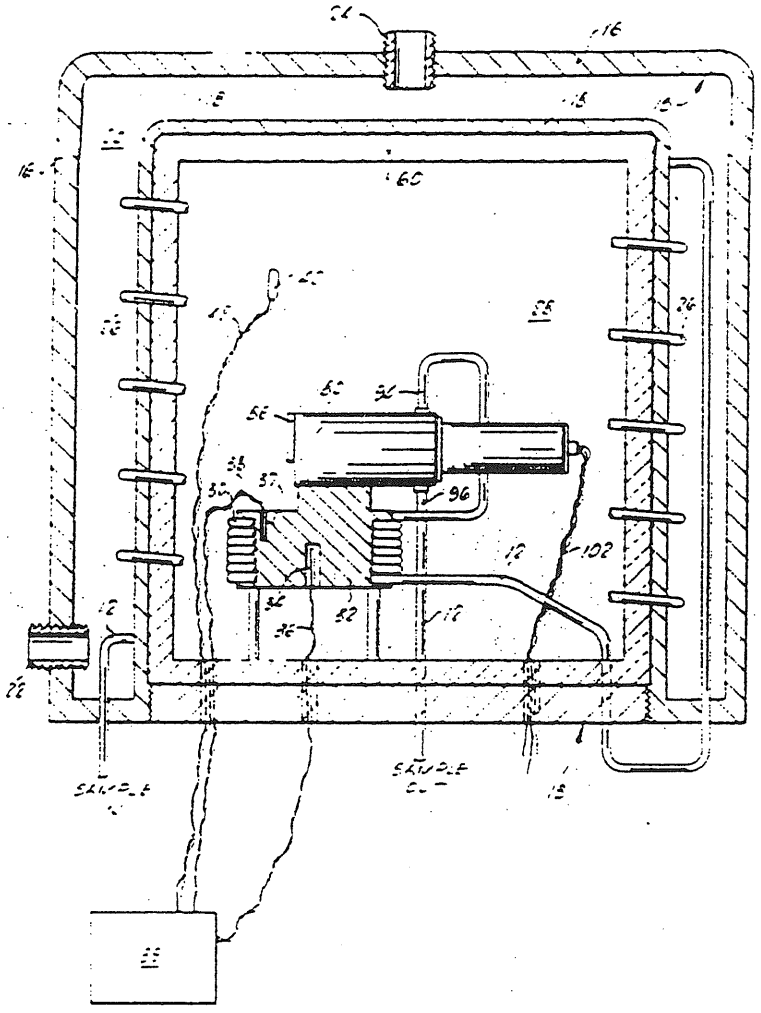

FIG 2

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Filed Jan. 12, 1962 4 Sheets-Sheet 3

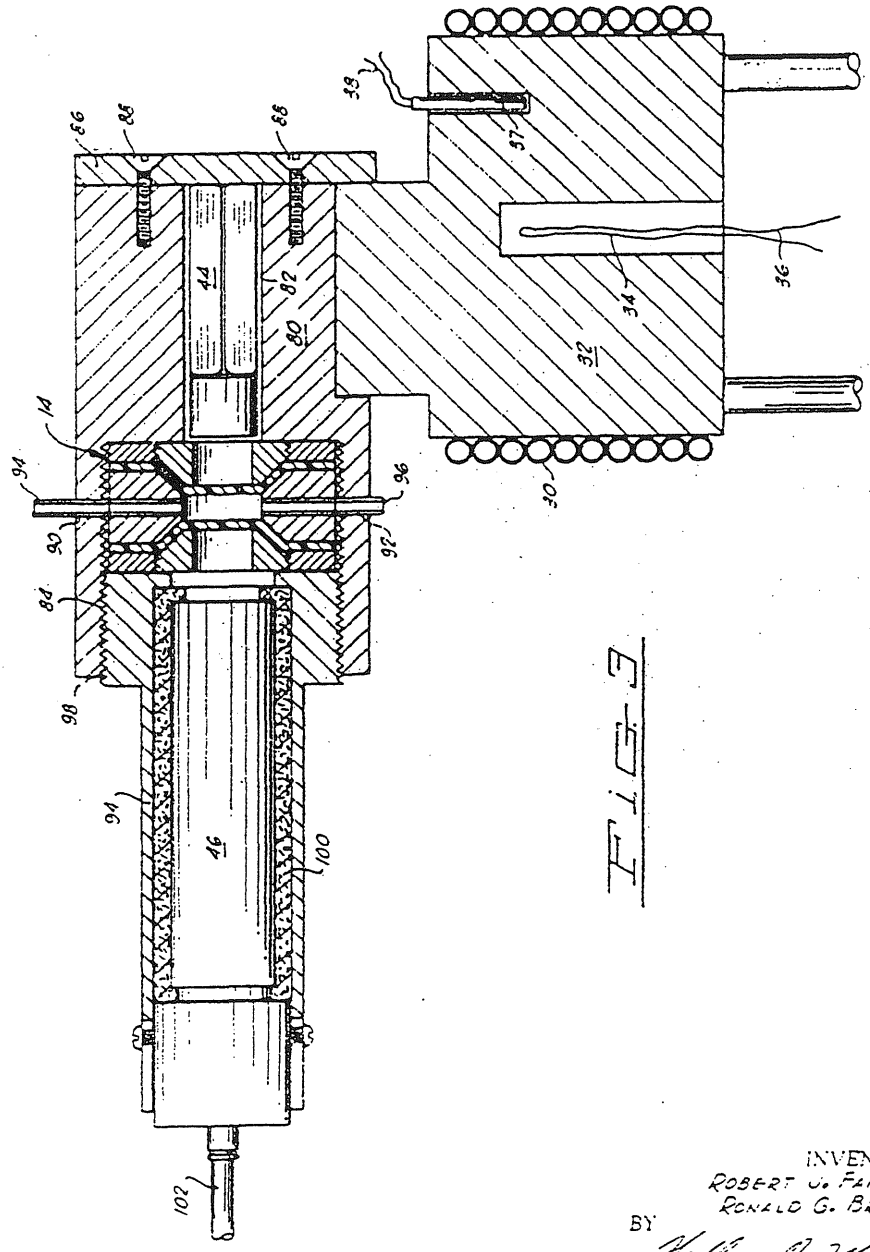

FIG 3

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Filed Jan. 12, 1962 4 Sheets-Sheet 4

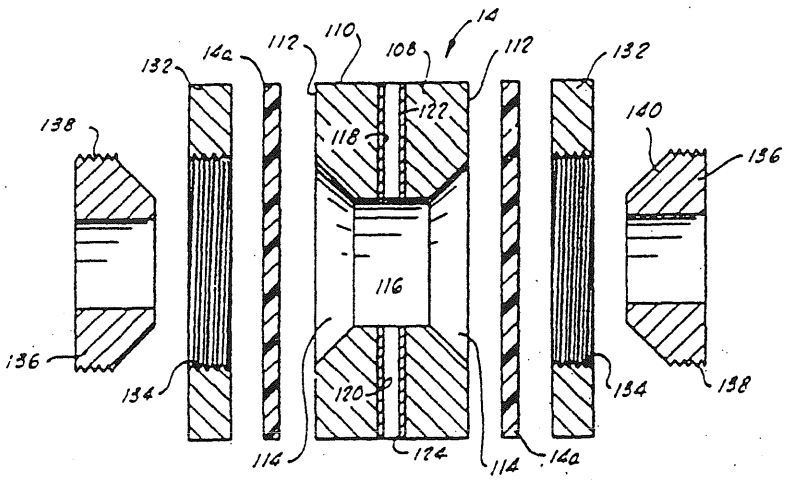

Fig. 4

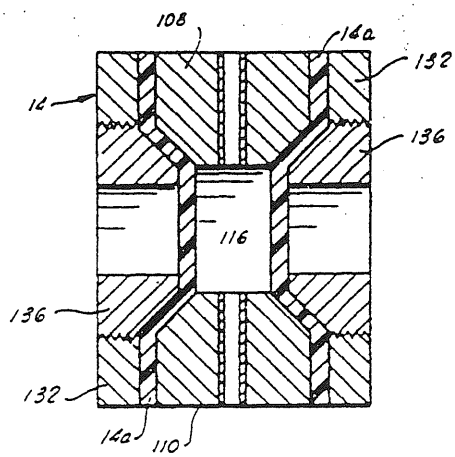

Fig. 5

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APPARATUS FOR DETERMINING THE CONCENTRATION OF ALUMINUM IN HYDROCARBON STREAMS BY THE USE OF K-CAPTURE RADIOACTIVITY

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8 Claims. (Cl. 250—43.5)

This invention relates, as indicated, to apparatus for determining the concentration of aluminum in a flowing hydrocarbon stream. More particularly, but not by way of limitation, the invention relates to apparatus which is especially well adapted for determining the concentration of a pyrophoric, highly reactive organo-aluminum compound in a flowing hydrocarbon plant stream, and for controlling the concentration of such organo-aluminum compound in such streams in accordance with such continuous determination.

In our co-pending application for U.S. Letters Patent Serial No. 165,853, filed of even date herewith and assigned to the assignee of the present invention, we describe a novel and highly useful process for determining the concentration of aluminum in hydrocarbon streams. Basically, the process described in the cited application comprises subjecting a sample taken from the stream to the impingement of certain types of radioactive emanations and determining the extent to which the passage of such emanations through the sample is attenuated by the presence of aluminum therein. The preferred source of such emanations is indicated in said application to be 10 millicuries of an iron 55 radioisotope which emits soft X rays having an effective wave length of about 2.05 A. The principle underlying the process is that of employing soft X rays of a wave length such that the other materials, primarily hydrocarbons, which are included in the hydrocarbon stream do not substantially impair or block the transmission of such soft X rays through a sample, while the aluminum, whether in bound or free form, carried by the stream, absorbs X rays of the selected wave length, and thus attenuates or blocks their transmission through the sample. The amount of attenuation, or the decrease in intensity, of the X rays is thus related to the amount of concentration of aluminum in the hydrocarbon stream. By measuring the extent of the attenuation or the decrease in the intensity of the X ray beam, this concentration may be continuously determined as a sample from the process stream is continuously passed through a sample cell where it is subjected to impingement by the X rays.

As mentioned in our cited co-pending application, the process described therein is particularly useful for evaluating the concentration of aluminum present in a hydrocarbon stream as one of several highly reactive, pyrophoric organo-aluminum compounds, such as aluminum trialkyls. To mention but one of the processes in which compounds of this type are employed, such aluminum trialkyls are currently being used in processes for producing relatively high molecular weight alcohols.

A number of unique problems are presented when the process of the invention covered in our co-pending application is applied to such highly reactive pyrophoric organo-aluminum compounds. First, the extremely reactive nature of such compounds requires that the materials of construction employed in the apparatus which is utilized in practicing the process be substantially inert or nonreactive with respect to such compounds. This presents an especially difficult problem with respect to the construction of the sample cell through which the sample

from the hydrocarbon stream is passed in order to subject the sample to impingement by the soft X rays. Such material of construction must not only be nonreactive to the organo-aluminum compounds carried by the hydrocarbon stream, but must also be transparent to X rays of the wave lengths which are utilized, and must be of sufficient mechanical strength to withstand relatively high bursting pressures and high temperatures.

A second problem which stems from the highly reactive, pyrophoric character of the organo-aluminum compounds is the danger inherent in handling such materials. For example, the aluminum trialkyls react violently with oxygen upon contact with the air and also react extremely vigorously with water. It is therefore essential that the apparatus employed be constructed to avoid contact between the organo-aluminum compounds and air, and also that solvents and liquid materials other than water, and in any case nonreactive with the aluminum trialkyl, be employed in the process. Moreover, it is highly desirable that the apparatus be constructed with adequate consideration given to certain mechanical safeguards against the contingency of an explosion occurring as the result of inadvertent contact between the organo-aluminum compound and the air.

As a final consideration in practicing the process described in the cited co-pending patent application, it is important that very close and accurate control of the temperature of the sample which is passed through the sample cell be maintained at all times in order that the accuracy of the determination may be maintained within the desired limits. Such fine and exact temperature control requires the utilization of very sensitive temperature control apparatus.

The present invention provides a system or apparatus for continuously determining the concentration of aluminum in a flowing hydrocarbon plant stream and for controlling the aluminum content of such streams in accordance with such continuous determination. The apparatus which is employed, though functioning equally well when used for the determination of many various types of aluminum compounds entrained in the stream, is especially well adapted to meet the particular problems which are posed in making such determination when the types of aluminum compounds entrained in the hydrocarbon stream are highly reactive, pyrophoric organo-aluminum compounds. Two salient and highly novel features of the invention reside in (a) the construction of the sample cell which is utilized for containing the sample as it is subjected to impingement by soft X rays emanating from a suitable radioisotope, and (b) the construction of the novel temperature control means for varying the temperature of the sample as may be desired, and for maintaining the temperature of the sample as it passes through the sample cell at a substantially constant value. The design of the temperature control means is also such that a considerable measure of safety against the possibility of explosion of the organo-aluminum compounds is provided. The apparatus permits the concentration of such organo-aluminum compounds to be continuously determined with a high degree of accuracy, and the construction of the apparatus is such that this accuracy is unimpaired by the undesirable reaction of the organo-aluminum compounds with any of the materials of construction utilized in the apparatus.

From the foregoing description, it will be apparent that the present invention provides a system for continuously determining the concentration of aluminum, whether bound or free, in a flowing hydrocarbon stream in a rapid, efficient and safe manner.

A more specific object of the present invention is to provide a novel sample cell for use in the process of

determining the concentration of aluminum in a flowing hydrocarbon stream by utilizing radioactive emanations, which sample cell does not interfere with the accuracy of such determination, and is characterized by a long and trouble-free operating life.

An additional object of the present invention is to provide a highly sensitive and efficient temperature control system for controlling the temperature of a liquid sample as it is continuously passed through a sample cell from a hydrocarbon stream containing an aluminum compound.

A further object is to provide a novel system for safely and continuously determining the aluminum content of a hydrocarbon plant stream carrying a highly reactive, pyrophoric organo-aluminum compound.

Other objects and advantages of the invention, in addition to those hereinbefore described, will become apparent to the reader, and will be better understood upon a reading of the following disclosure in conjunction with a perusal of the following drawings which illustrate our invention.

In the drawings:

FIGURE 1 is a liquid flow and electronic circuit diagram illustrating the system of the invention.

FIGURE 2 is a view partially in section and partially in elevation of the measuring head which constitutes a portion of the system of the invention.

FIGURE 3 is an enlarged sectional view of the isothermal block, sample cell, radioisotope source, and Geiger-Müller tube which are employed in a preferred embodiment of the invention.

FIGURE 4 is an exploded sectional view of the sample cell which is utilized in a preferred embodiment of the invention.

FIGURE 5 is a sectional view through the center of the sample cell shown in FIGURE 4 with the sample cell in its assembled status.

Referring now to the drawings in detail, and particularly to FIGURE 1, reference character 10 designates a pipeline utilized in a process such as the alcohol synthesis process hereinbefore described, for carrying an organo-aluminum reactant entrained in a hydrocarbon solvent. In the alcohol synthesis process hereinbefore mentioned, the organo-aluminum compound utilized is an aluminum trialkyl, and the hydrocarbon carrier preferably is a kerosene fraction having an API gravity of between 39 and 43. Other hydrocarbon solvents which might be employed include, but are not limited to, a petroleum naphtha fraction containing little or no unsaturated or aromatic hydrocarbons and sold under the tradename Soltrol, and also a substantially pure isooctane stream. The primary considerations in the selection of the hydrocarbon carrier are that it not be reactive with the aluminum trialkyl, and that it contain predominately compounds composed only of carbon and hydrogen atoms. A sampling line or conduit 12 communicates with the process line 10 for conducting the sample to be analyzed from the process line into a sample cell which is located in a measuring head 13 and which is designated generally in FIGURE 1 by reference character 14. The sample cell 14 is provided with a pair of opposed cell faces 14*a* hereinafter described in detail.

Enroute to the cell 14, sampling conduit 12 passes through the hollow cooling jacket 15 of the measuring head 13. The cooling jacket 15 is of double-walled construction, having an outer wall 16 and an inner wall 18. The material of construction of the cooling jacket 15 is preferably aluminum metal. This provides further assurance against the deleterious contamination of the sample stream, and also provides a material which is nonreactive with the aluminum trialkyl in the event a leak should occur in the sampling conduit 12. Moreover, the aluminum is relatively inexpensive and is of relatively light weight to permit the measuring head to be transported relatively easily from one location to another as may be necessary under differing plant conditions.

The outer and inner walls, 16 and 18, respectively, define a chamber 20 through which a suitable coolant liquid is circulated by way of the coolant inlet conduit 22 and coolant discharge conduit 24. Although other materials may be utilized as a coolant, I prefer to use kerosene for this function because of its ready availability, and its inertness to reaction with the organo-aluminum compounds entrained in the hydrocarbon stream. Materials which react vigorously with the organo-aluminum compounds, such as water, should not be utilized as the cooling material because of the explosion hazard which is involved in such use.

It will be noted that the double-walled construction of the cooling jacket 15 of the measuring head 13 in conjunction with the generally cylindrical geometric configuration of the measuring head provides a safeguard against the occurrence of excessive damage or injury to operating personnel should there occur an explosion at any point inside the measuring head.

After the sampling conduit 12 enters the measuring head 13, it describes a number of convolutions 26 around the internal wall 18 and in the chamber 20 of the cooling jacket 15. There is thus afforded an enhanced opportunity for heat exchange between the sample within the conduit 12, and the coolant material circulating inside the chamber 20. In general, the sample from the process stream will be relatively warm as it enters the cooling jacket 15, having an average temperature of between about 140 and 180° F. The kerosene which is circulated through the chamber 20 in the cooling jacket 15 is maintained at a temperature of approximately 90 to 110° F. so that the temperature of the sample is lowered to this value before the sampling conduit 12 leaves the chamber 20 and enters the space 28 existing inside of the inner wall 18 of the cooling jacket 15. The step of initially cooling the sample to a temperature of between 90 and 110° F. is an important step of the process, and the apparatus which is utilized for achieving this lowering of the temperature is therefore considered to be a salient feature of the invention.

After the sampling conduit 12 enters the space 28 within the inside wall 18 of the cooling jacket 15, it is passed in continuous convolutions 30 around an isothermal block 32. The isothermal block 32 is internally heated by heating elements 34 (shown in FIGURE 2) which are connected to electrical leads 36 passing out through the bottom of the measuring head 13. The temperature of the isothermal block 32 is precisely controlled by means of a thermistor 37 placed in the top of the block, and connected by leads 38 to a control device 39 which controls the heating elements 34 located inside the block. As a further element for accurately controlling the temperature of the isothermal block and the air in the space 28, a thermocouple 40 is provided inside the space 28, and is connected by electrical leads 42 to the heating element control device 39 located outside the measuring head 13. The manner in which the thermistor 37, heating elements 34, and thermocouple 40 function to accurately and safely control the temperature of the isothermal block 32 is subsequently explained in detail.

After passing in heat exchange relation to the isothermal block 32, the sample enters the sample cell 14 where it is subjected to the impingement of soft X rays from the radioisotope source 44. In the preferred embodiment of the invention, the source material which is utilized is a 5 to 50 millicurie sample of iron 55. The soft X rays which are emitted from the iron 55 source 44 are transmitted through the cell 14 via the cell faces 14*a* of the sample cell 14, and are then detected by a suitable sensing or detecting instrument, such as a Geiger-Müller tube 46 disposed on the opposite side of sample cell 14 from the iron 55 source. The Geiger-Müller tube 46

is sensitive to the soft X rays and provides a small positive pulse for each X ray received.

The pulses from the Geiger-Müller tube 46 are transmitted to a preamplifier 48 which may be located outside the measuring head 13, but which preferably is located in a shielded position in the space 28 inside the wall 18 of the cooling shell 15. In FIGURES 1 and 2, the preamplifier is shown outside the measuring head in order to lend clarity to the drawings and the discussion. The preamplifier 48 amplifies and inverts the pulses received from the Geiger-Müller tube 46 and then passes the amplified, inverted pulse signals into a rate count meter 50 which provides an output proportional to the time average of the signal pulses. The zero reading and span of the rate meter 50 may be made adjustable by the provision of suitable span-zero control circuitry if desired. The output from the rate meter 50 is visually displayed on the recorder 52, and the the output signal may also be directed to a suitable control device (not shown) such as a proportioning pump or a solenoid valve for controlling the addition of the aluminum trialkyl or kerosene to the process stream in response to the aluminum trialkyl concentration which is determined to exist at any instant.

After leaving the sample cell 14, the sample flows out of the space 28 in the sampling conduit 12 and is returned to the process line 10. The fluid time constant for the system is approximately four minutes; that is, this is the time required for the sample to flow into the sample cell 14 from the process line 10. The flow rate of the sample through the system is about 100 ml. per minute. It will thus be seen that a continuous determination of the concentration of aluminum in process streams may be carried out with very little time lag occurring between initial diversion of the sample from the process stream 10, and final readout of the concentration value upon the recorder 52. Those skilled in the art will, of course, appreciate that an initial calibration of the apparatus using samples contianing known concentrations of aluminum is required before commencing the determinations.

In the description of the invention to this point, reference has been made to the schematic flow diagram of FIGURE 1. This description has served to provide a general understanding of the system as a whole, and the manner in which the sample stream flows through the system and the pulse signals developed by the Geiger tube 46 are directed to final readout upon the recorder 52. The more detailed, less schematic representations of certain components of the systems which are illustrated in FIGURES 2, 3 and 4 will next be described in order to more succinctly point out the various novel elements of the invention and their functioning.

In FIGURE 2 of the drawings, the measuring head 13 of the system is illustrated. It will be perceived that the outer and inner walls, 16 and 18, respectively, of the cooling jacket 15 are of relatively thick structure to provide a safeguard against the possibility of explosion of the organo-aluminum compounds circulating in the sampling conduit 12. It will be recalled from the previous discussion that the kerosene circulating in the space 20 between the inner and outer walls of the cooling jacket 15 is relatively cool as compared to the temperature of the space 28 inside the innermost wall 18 of the cooling jacket. In order to prevent the existence of any substantial temperature gradient across the space 28 between the isothermal block 32 and the inner wall 18 of the cooling jacket 15, a relatively thick layer of a thermally insulating material 60 is secured to the inside face of the inner wall 18. This provides a relatively high degree of assurance that the temperature in the space 28 surrounding the isothermal block 32 will be maintained at approximately the same temperature as the isothermal block once the warmup period of the system has been completed.

Also from the previous description, it will be recalled that very close control of the temperature of the sample is a factor of utmost importance in achieving a high degree of accuracy in the determination of the aluminum concentration in the hydrocarbon stream. This is true whether the sample in which the aluminum is to be determined contains a highly reactive, pyrophoric organo-aluminum compound, or other aluminum compounds, or even free aluminum. For example, we have found that a temperature variation of 0.5° F. in the temperature of the sample passing through the sample cell 14 may cause an error of 0.5 percent in the aluminum determination. In order to provide the positive and accurate control which is required, a novel temperature control system has been devised which permits the sample to be brought well within the 0.5° F. permissible deviation over a range of from 115 to about 200° F. Actually, the maximum upper limit of the temperature range which may be employed is dictated primarily by the ability of the material of construction of the cell 14 to withstand such maximum temperature, and the boiling point of the solvent or hydrocarbon in which the aluminum or aluminum compounds are entrained.

As the sample is passed into the space 28 within the inside wall 18 of the measuring head 13, the sample carrying conduit 12 is passed around the isothermal block 32 in a plurality of convolutions 30 which are soldered to the block with a solder having a high coefficient of thermal conductivity. As the sample first enters these convolutions 30, its temperature will be slightly lower than that of the isothermal block by virtue of having passed in heat exchange relation to the cooler kerosene circulating within the cooling jacket 15. However, the heat exchange between the sample and the isothermal block 32 soon results in the sample being brought up to the temperature of the block.

In order to heat the isothermal block to the required temperature and maintain such temperature at a substantially constant value, a plurality of heating elements 34 are positioned within the block and are connected by electrical leads 36 to a controller device 39 located outside the measuring head. Also connected to the controller device is a thermistor 37 which is placed in the top of the isothermal block 32 and which continuously senses the temperature of the block. The controller device 39 is responsive to the temperature of the block as sensed by the thermistor 37 to energize and de-energize the heating elements 34 as necessary in order to maintain the temperature of the block constant. Of course, any temperature to which it is desired to heat the sample may be set into the controller device, and after allowing an adequate time for the isothermal block to reach the desired temperature, maintenance of this temperature is automatic.

As a safety feature of the invention, and as a further assurance that the controller device 39, heating elements 34 and isothermal block 32 are functioning properly, a thermocouple 40 is positioned in the space 28 inside the inner wall 18 of the cooling jacket 15, and is disposed at some location intermediate between the isothermal block 32 and the insulation 60 which covers the inner surface of the wall 18. The thermocouple 40 is connected to the controller device 39 by electrical leads 42. The function of the thermocouple 40 is to sense the temperature of the air in the space 28 surrounding the isothermal block 32, and to transmit a signal to the controller device 39 corresponding to such sensed temperature. A suitable control mechanism (not seen) is provided in the controller device 39 for semipermanently and automatically breaking the circuit between the controller device and the heating elements 34 when the temperature in the space 28, as sensed by the thermocouple 40, exceeds a certain predetermined maximum. Thus, if the controller should in some manner malfunction, permitting the temperature of the isothermal block to run away, the thermocouple 40 will sense the unusual increase in temperature and will deactivate the

controller device. Re-establishment of the operation of the controller device 39 must then be manually effected.

The precision control of the sample temperature which is attainable with the present invention is, as has been indicated, one of the invention's most important features. We have found that the temperature control attainable with the system is well within the 0.5° F. temperature fluctuation which can be tolerated in achieving an accuracy of ±0.5% in the aluminum determination. By first lowering the temperature of the sample in sampling conduit 12 to slightly below the desired testing temperature by heat exchange with the cooling medium in space 20, and then raising it by use of the isothermal block 32, the temperature may be brought smoothly and easily up to the desired value without overshooting or hunting. In this way, we have maintained sufficiently close temperature control to repeatedly obtain an accuracy of ±0.1% in the determination of the aluminum trialkyl content of hydrocarbon streams.

The arrangement of the sample cell 14, the Geiger-Müller tube 46, and the iron 55 radiation source 44 is illustrated in FIGURE 3. A housing 80 is secured to the top of the isothermal block 32, and is provided with a bore 82 at one end thereof for receiving the capsule containing the iron 55 source material 44. At its opposite end, the housing 80 is provided with a larger, internally threaded counterbore 84 for receiving the sample cell 14 and the Geiger-Müller tube 46. After the iron 55 radiation source 44 is placed in the bore 82, an end plate 86 is placed over the bore and retains the radiation source in position inside the housing 80. Suitable screws 88 are used for securing the end plate in position. It will be noted that in this position, the iron 55 radiation source is shielded to prevent unnecessary exposure of operating personnel to the radioactive emanations from such source.

In assembling the radiation source, cell, and detector elements, the cell 14 is initially placed in the counterbore 84 of the housing 80, and the inlet and outlet ports of the cell are aligned with an inlet opening 90 and a discharge opening 92 formed in the housing 80. These openings are, in turn, connected to the sampling conduit 12. A housing 94 which contains the Geiger-Müller tube 46, and which is threaded at one of its ends as indicated by reference character 98, is then threaded into the counterbore 84 of the housing 80 until it abuts against the sample cell 14. In this way, the sample cell 14 is retained in fixed position relative to the Geiger-Müller tube 46 and the iron 55 radiation source 44. It will be noted that the Geiger-Müller tube 46 is cushioned in its housing 94 by a layer of felt material 100 which is packed into the space existing between the tube and the walls of its housing 94. The electrical lead for conducting the pulse signals from the Geiger-Müller tube 46 to the preamplifier 48 is designated by reference character 102.

It will be noted that the construction of the assembly which includes the iron 55 radiation source 44, the sample cell 14, the Geiger-Müller tube 46 and its housing 94 is such that relatively little space is occupied by these components of the system, and the benefit of maximum safety to operating personnel is obtained. Moreover, the sample cell 14 is positioned in relatively close proximity to the isothermal block 32, and is located inside a housing 80 which is in thermal conducting contact with the isothermal block. This construction assists in permitting the sample cell 14 to be retained at the temperature of the isothermal block 32 at all times during the operation of the system.

The construction of the novel sample cell 14 of the present invention is illustrated in detail in FIGURES 4 and 5. The cell 14 comprises a block 108 of metallic material, preferably aluminum, which is provided with a generally cylindrical external periphery 110, and a pair of opposited, parallel end surface 112, each of which end surfaces is provided with a centrally located frusto-conical recess 114. The recesses 114 are interconnected by a large bore 116 which extends through the block therebetween, and which, for purposes of explanation, will hereinafter be referred to as the sample chamber. The block 108 is further provided with a radially extending sample inlet port 118 which communicates with the sample chamber 116 at one side thereof, and an opposed, radially extending sample discharge port 120 which communicates with the sample chamber 116 on the opposite side thereof. In a preferred embodiment of the invention, a sample inlet conduit 122 is pressed into the sample inlet port 118, and a sample discharge conduit 124 is pressed into the sample discharge port 120.

To complete the description of the sample cell construction, a pair of cell faces 14*a* are initially placed in flatly abutting relation to the parallel end surfaces 112 of the cell block 108. A pair of flat retainer plates 132 are then placed against the exposed planar surfaces of the cell faces 14*a* and are secured through the cell faces to the end surfaces 112 of the metallic block 108. Each of the retainer plates 132 in provided with a threaded bore 134 therethrough which corresponds in diameter to the diameter of the base or largest diametric dimension of each of the frusto-conical recesses 114, and the bore 134 of each of the retainer plates 132 is aligned with one of the recesses when the plates are secured in position.

In addition to other properties which must be possessed by the materials of construction of the cell faces 14*a* and which are subsequently described, this material must be sufficiently flexible and ductile to permit it to be stretched or distorted from the monoplanar position which it initially assumes to a configuration conforming to the contours of the frusto-conical recesses 114. With the cell face material possessing this property, a pair of plugs 136 which each have a threaded cylindrical outer periphery 138, and a tapered end 140, may then be threaded into the threaded bores 134 in the retainer plates 132 until the tapered ends 140 of the plugs abut against the cell faces 14*a*. Further threading of the plugs 136 into the bores 134 of the retainer plates 132 distorts or presses the cell faces 14*a* into the frusto-conical recesses 114 formed in the opposing end surfaces 112 of the cell block 108. When the plugs 136 are threaded into the retainer plates 132 until their ends are flush with the exposed ends of the retainer plates, the sample cell assembly is completed and the cell 14 appears as shown in FIGURE 5.

The distance between each of the cell faces 14*a* in the cell 14 is of considerable importance, since the amount by which the sample attenuates the soft X ray beam is directly dependent upon the amount of sample through which the beam must pass. We have found that excellent sensitivity may be obtained in the determination of aluminum trialkyls when a cell thickness of about 5 mm. is utilized. However, cell thicknesses between 2 and 7 mm. can also be employed and the particular cell thickness selected will be dependent in any case to a large extent upon the nature of the sample which is to be circulated through the cell. In general, cells thinner than 2 mm. seem to cause a marked loss of sensitivity, while cells thicker than about 7 mm. require the employment of a substantially stronger or more intense source of radiation.

The material of which the cell faces 14*a* are constructed is a critical factor in the proper construction of the system and constitutes a salient feature of the invention. As has been previously mentioned, a certain amount of flexibility and ductility must characterize this material when the prefered cell construction illustrated in FIGURES 4 and 5 is utilized. However, even when modified embodiments not requiring the extreme distortion of the cell faces as shown in FIGURES 4 and 5 are employed, a number of requirements still must be met by the cell face materials. Since any interference of the cell face material with the passage of the soft X rays therethrough will result in impairment of the sensitivity of the alumi-

num concentration determination and probable decrease in accuracy, it is essential that the cell face material be substantially transparent to X rays of the wave length utilized in the instant invention—about 2 A. This requirement elliminates the usual metals, as well as those plastics which contain fluorine or heavier elements. In effect, the cell face material should not contain atoms of higher atomic number than oxygen, and even those containing oxygen attenuate the soft X ray beams to an undersirable extent.

The material of which the cell faces 14*a* are constructed must also be inert or nonreactive with respect to the sample and its components. When a highly reactive, pyrophoric organo-aluminum compound, such as the aluminum trialkyls, is present in the sample, this requirement becomes of extreme importance. We have found that many of the plastic materials which appear to possess the other properties requisite of the cell face material fail to possess sufficient inertness with respect to aluminum trialkyls to be used in the construction of sample cells intended to receive samples carrying this type of compound.

Because of the relatively high temperatures to which the sample may be heated, it is also necessary that the cell face material possess good thermal stability over the range of anticipated operating temperatures. The stability of the material at higher temperatures must be maintained even under operating pressures as high as 100 lbs. per square inch, since the pressure in the process line 10 and sampling conduit 12 may sometimes attain this magnitude. Any slight distortion of the cell faces at these temperatures and pressures will result in a variance of the effective thickness of the cell 14, and since the amount of attenuation of the X ray beam by the sample in the cell is directly proportional to the cell thickness, such distortion will cause the determination results to be erratic and inaccurate.

Lastly, it is desirable that the cell faces 14*a* be made as thin as possible without sacrifice of their mechanical strength and thermal stability, and without rendering them pervious to one or more of the chemical constituents of the sample.

We have found that a material which meets all of the aforementioned requirements, yet which is relatively inexpensive as compared to several other suitable materials, is high density polymerized polyethylene sold under the tradename of Type No. 2 Marlex by the Phillips Petroleum Company of Bartlesville, Oklahoma. This is the material which has been employed in the construction of the preferred embodiment of the sample cell 14 illustrated in FIGURES 4 and 5. When Type No. 2 Marlex is used as the material of construction of the cell faces 14*a*, a thickness of 0.015 inch may be employed for the sheet of Marlex at each face

Other materials which may be utilized in the construction of the cell faces 14*a* include beryllium. industrial diamond, certain types of graphite, polypropyiene and high molecular weight polyisobutylene.

From the foregoing description of the invention, it will be perceived that the present invention provides a system for determining the concentration of all types of aluminum compounds in various hydrocarbon streams. Included in such compounds are highly reactive, pyrophoric organo-aluminum compounds which normally require extreme caution in handling. Change or variation in the hydrocarbon solvent which carries the aluminum compound to be determined requires a minimum of recalibration of the instrument, since the curves of aluminum concentration vs. counts per minute signalled by the Geiger-Müller tube are of substantially the same slope, regardless of the hydrocarbon solvent used, provided all other paramaters, such as cell thickness and temperature are held constant. As an example of the results attainable with the system of the invention, the following table compares the values for the aluminum concentration in three different

samples as such values were obtained by wet chemical analysis and by the apparatus of the present invention In each sample, a different concentration of aluminum triethyl in Soltrol was provided.

Sample	Wet Chemical Analysis, Percent Al	Soft X Ray, Percent Al
1	4.65	4.62
2	4.36	4.38
3	4.16	4.16

The table reflects the excellent accuracy which is attainable with the present invention. It will also be apparent, of course, that the saving in time and required operating personnel which may be realized by using the apparatus of the invention, as opposed to determining the aluminum concentration by wet chemical analysis, is a factor greatly favoring the widespread acceptance and use of the invention.

Although a preferred embodiment of the invention has been hereinbefore described by way of example, a number of changes and modifications in many of the components and elements of the system may be made without departure from the basic principles underlying the invention. For example, several satisfactory cell face materials have been suggested which might be used in place of the Marlex which is used in the preferred embodiment. Also the type of electronic readout system which is employed for converting the pulses produced by the Geiger-Müller tube to visible indicia could also be altered or refined to some extent in order to portray the desired information in a different or more acceptable form. The Geiger-Müller tube might itself be replaced by other types of detecting devices such as a scintillation crystal In fact, the use of the latter type of detector may be highly desirable under circumstances where there is very low attenuation of an extremely intense beam of soft X rays, such as where an amount of radioisotope exceeding 20 millicuries is used, and the sample contains a very low concentration of aluminum. This is because the detecting efficiency or sensitivity of the Geiger-Müller tube appears to fall off somewhat at count levels exceeding 50,000 counts per minute.

The suggested modifications of the invention, as well as a number of other possible changes, will be appreciated by those skilled in the art. Insofar as all such modifications, changes and innovations are employed in an apparatus or system which retains and relies upon the novel, inventive principles hereinbefore described, such apparatus or system is deemed to be included within the spirit and scope of the present invention, except as the same may be necessarily limited by the appended claims

We claim:

1. Apparatus for determining the concentration of aluminum in a carrier material comprising:

a sample cell for holding a sample, the aluminum concentration of which is to be determined, said cell having a pair of opposed cell faces which are substantially transparent to soft X rays having a wave length of about 2 A., and which are nonreactive with the aluminum compounds in said carrier material;

a radioactive isotope source of said soft X rays positioned adjacent said cell for transmitting soft X rays through said cell via said cell faces;

detector means for detecting soft X rays transmitted through said cell and producing signals indicative of the number of said transmitted soft X rays detected by said detector means;

readout means connected to said detector means for portraying visible indicia indicative of the number of soft X rays transmitted through said cell; and

means for controlling the temperature of the sample placed in the sample cell, said control means comprising:

heat exchange means for lowering the temperature of said sample before the sample is placed in said cell;

second heat exchange means for raising the temperature of said sample after the sample has passed through said first-mentioned heat exchange means and before the sample enters said cell; and

means for varying the amount of heat exchanged between said second heat exchange means and said sample whereby the temperature of the sample as it enters said cell may be adjusted as desired.

2. Apparatus as claimed in claim 1 wherein said radioactive isotope source comprises iron 55.

3. Apparatus as claimed in claim 1 wherein said detector means comprises a Geiger-Müller tube.

4. Apparatus as claimed in claim 1 wherein said readout means comprises:

amplifying means for amplifying the signals produced by said detector means;

rate averaging means connected to said amplifying means for receiving the amplified signals from said amplifying means and producing output signals proportional to the average number of signals received from said amplifying means in a given time; and

a recording device responsive to the output signals from said rate averaging means for recording a visible trace indicative of the number of soft X rays transmitted through said cell.

5. Apparatus as claimed in claim 1 wherein said second heat exchange means comprises:

an isothermal block;

a tubular conduit coiled around said block and connected to said sample cell for conveying the sample to said sample cell;

and an insulated chamber surrounding said isothermal block for maintaining the space around said isothermal block at substantially the same temperature as said block.

6. Apparatus as claimed in claim 5 wherein said means for varying the amount of heat exchanged between said second heat exchange means and said sample comprises:

a heating element in said isothermal block for varying the temperature of said block;

a thermistor in said isothermal block for sensing variations in the temperature of said block;

a control device connected to said thermistor and said heating element for energizing and de-energizing said heating element in response to variations in the temperature of said isothermal block as sensed by said thermistor; and

a thermocouple in said space inside said insulated chamber and connected to said control device for monitoring the performance of said thermistor, heating element and control device.

7. A system for continuously determining the concentration of aluminum in a flowing hydrocarbon stream comprising:

a sample cell for continuously receiving a sample from a flowing stream and having windows substantially transparent to soft X rays having a wave length of about 2.05 A. and constructed of a material which is substantially unaffected by sample temperatures of at least 180° F. and is nonreactive with the materials carried in said hydrocarbon stream;

a source of radioactive emanations positioned adjacent said cell for transmitting said emanations through the windows of said cell and the sample therein;

a detector for detecting radioactive emanations transmitted through said cell and sample and producing signals in response to said detected emanations;

means for adjusting the temperature of said sample prior to the passage of the sample into the cell; and

means for maintaining the temperature of said sample substantially constant at the temperature to which the sample is adjusted, said temperature maintaining means comprising:

(a) a double-walled cooling jacket containing a cooling medium between said walls and defining a space inside the innermost wall thereof;

(b) an isothermal block in said space; and

(c) a sampling conduit connected between said flowing hydrocarbon stream and said cell and passing between the walls of said cooling jacket in heat exchange relation to said cooling medium and passing in convolutions around said isothermal block in abutting contact therewith whereby the temperature of said sample may first be lowered by passage through said cooling jacket, then raised and made constant by heat exchange with said isothermal block; and

readout means connected to said detector means for portraying visible indicia indicative of the extent to which emanations have been transmitted through said sample and cell.

8. A system as claimed in claim 7 wherein the inner surface of the innermost wall of said cooling jacket is covered with a thermally insulating material so that the temperature of the air around said isothermal block inside said space may be maintained at a temperature substantially equivalent to the temperature of the isothermal block.

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ARCHIE R. BORCHELT, *Examiner.*

June 11, 1968 G. GOULD 3,388,314

APPARATUS FOR GENERATING RADIATION OF FREQUENCIES HIGHER THAN THOSE OF LIGHT

Filed Aug. 21, 1967 8 Sheets-Sheet 1

Fig. 1.

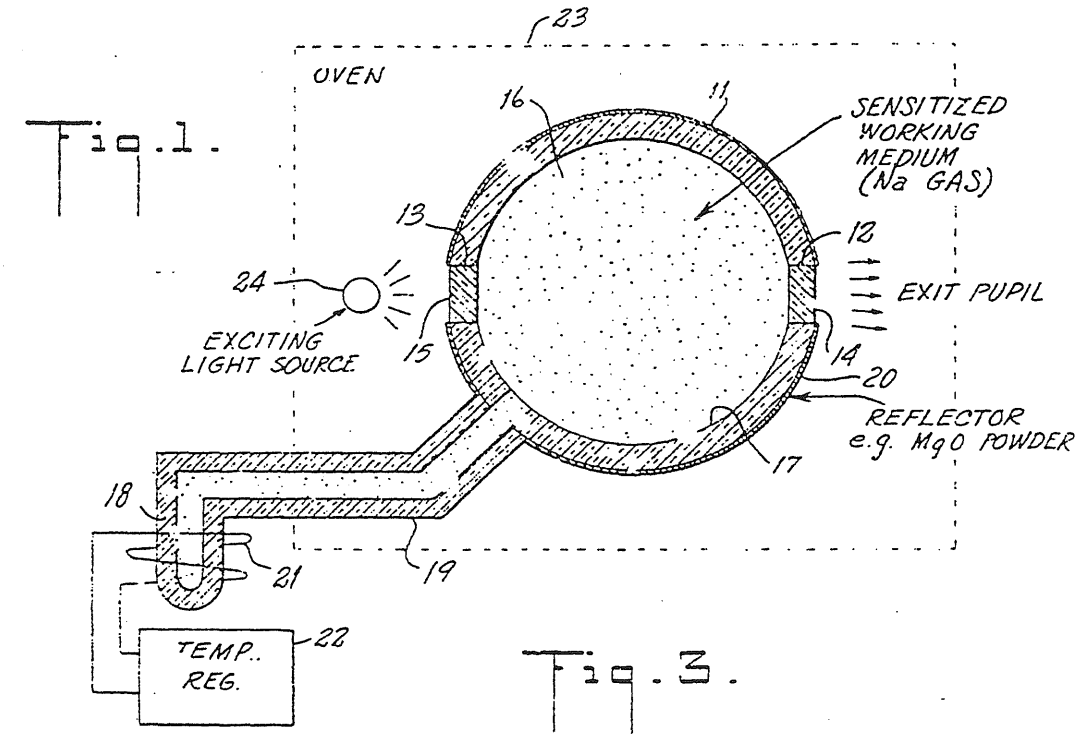
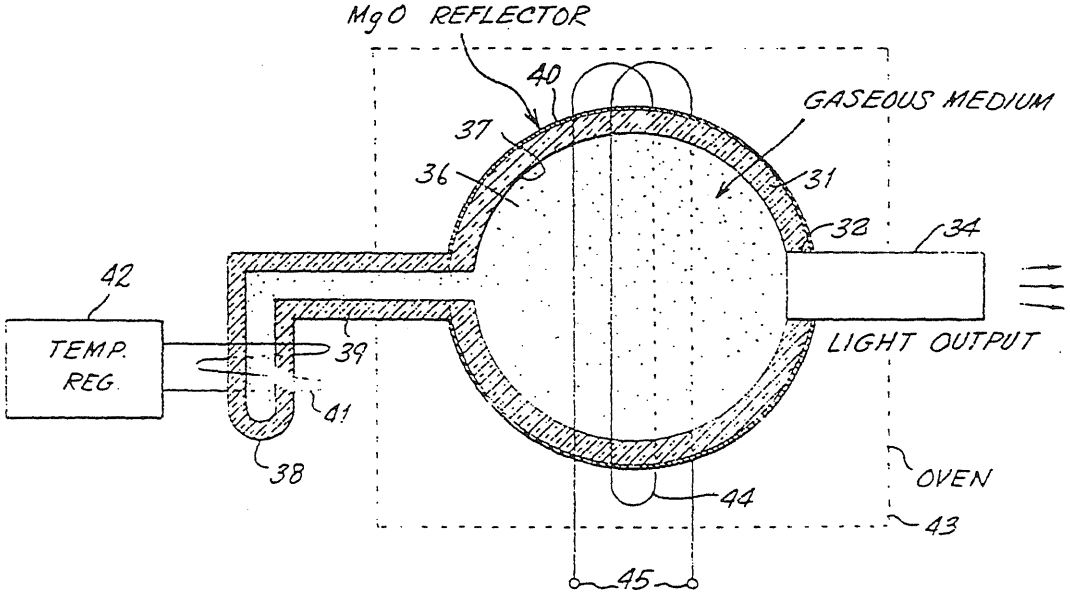


Fig. 3.



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APPARATUS FOR GENERATING RADIATION OF FREQUENCIES HIGHER THAN THOSE OF LIGHT

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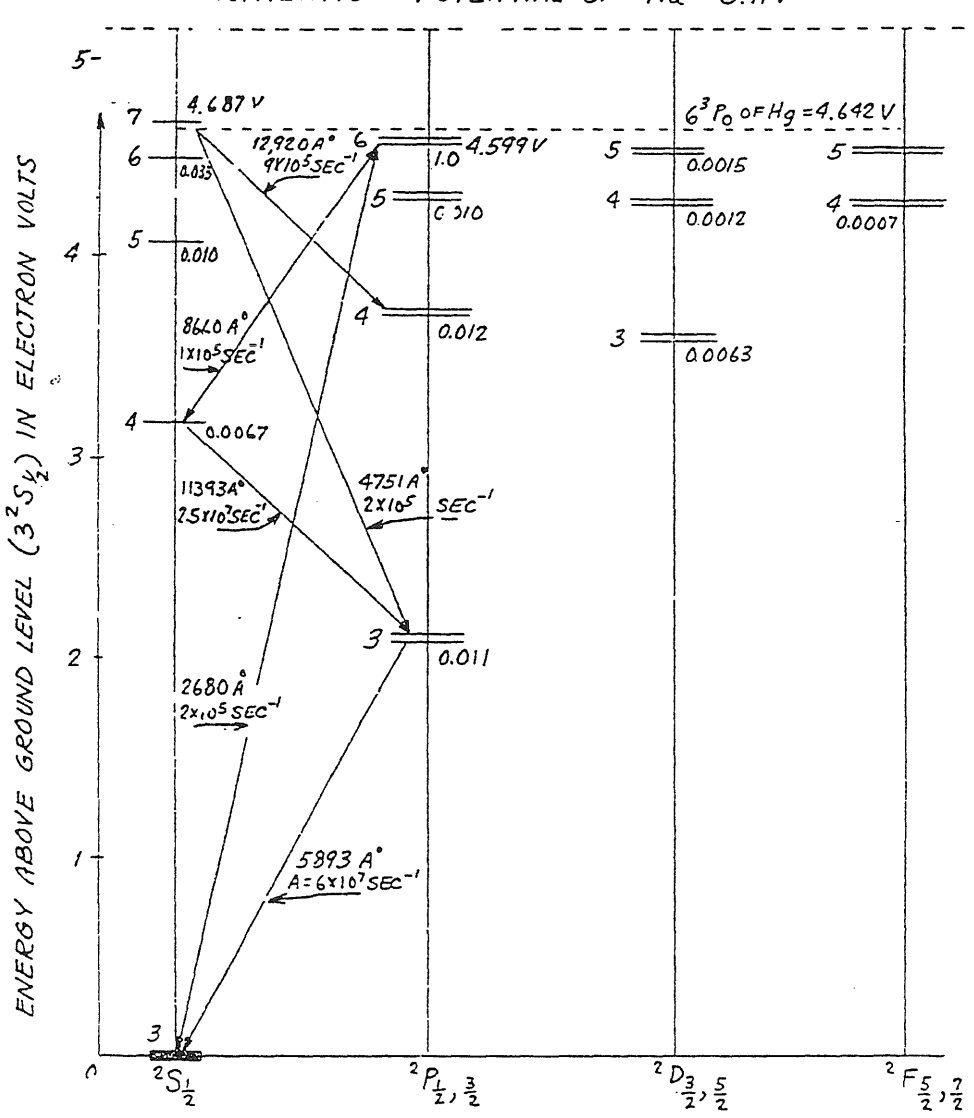
Fig. 2.



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APPARATUS FOR GENERATING RADIATION OF FREQUENCIES HIGHER THAN THOSE OF LIGHT

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Fig. 4.

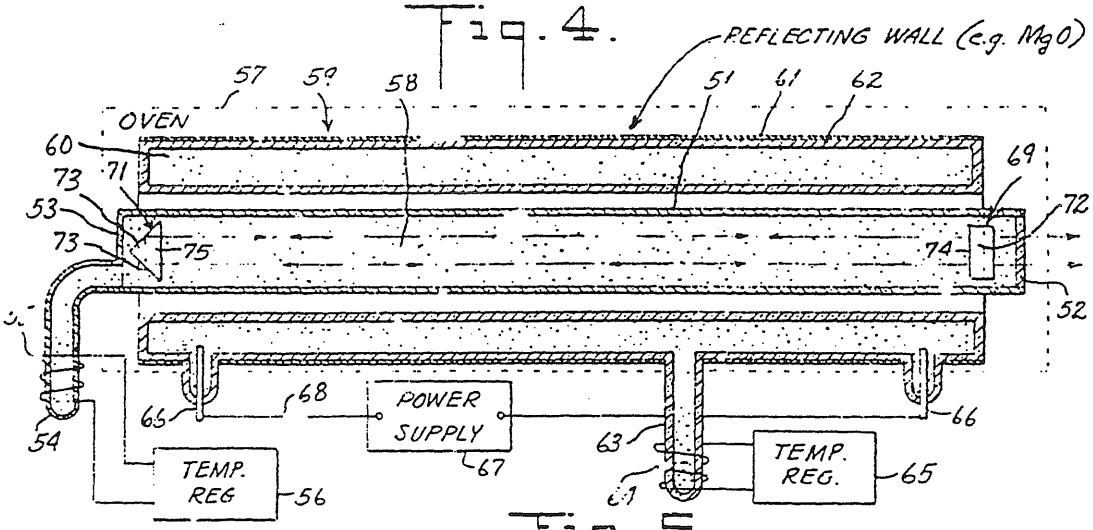


Fig. 5.

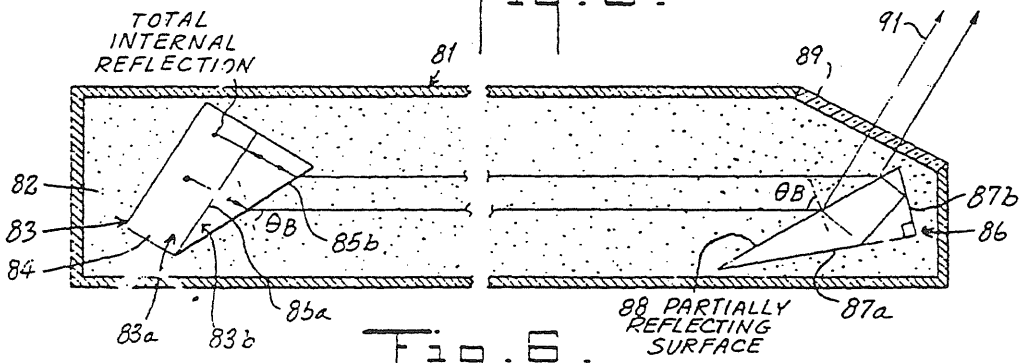
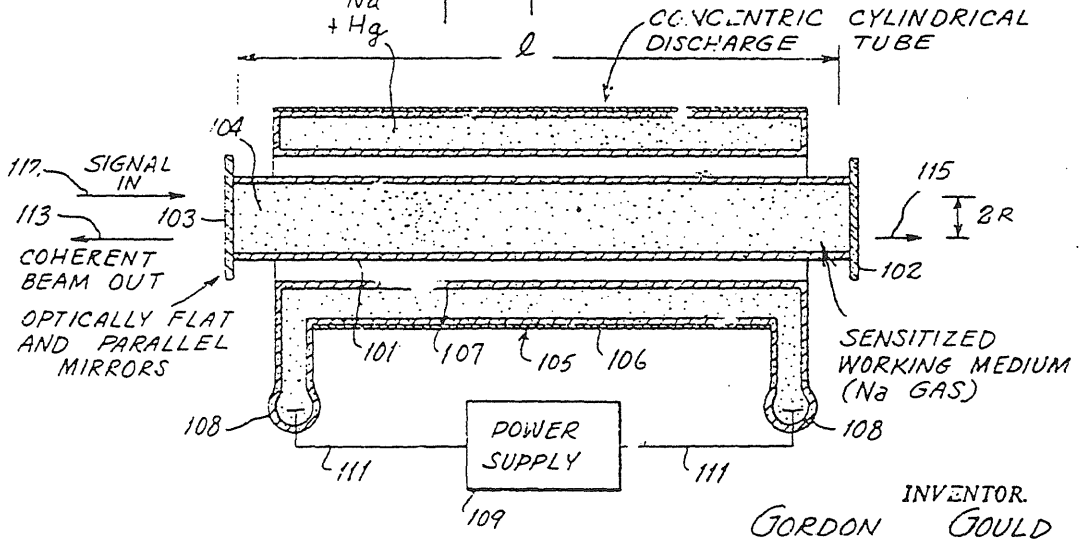


Fig. 6.



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APPARATUS FOR GENERATING RADIATION OF FREQUENCIES HIGHER THAN THOSE OF LIGHT

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Fig. 7.

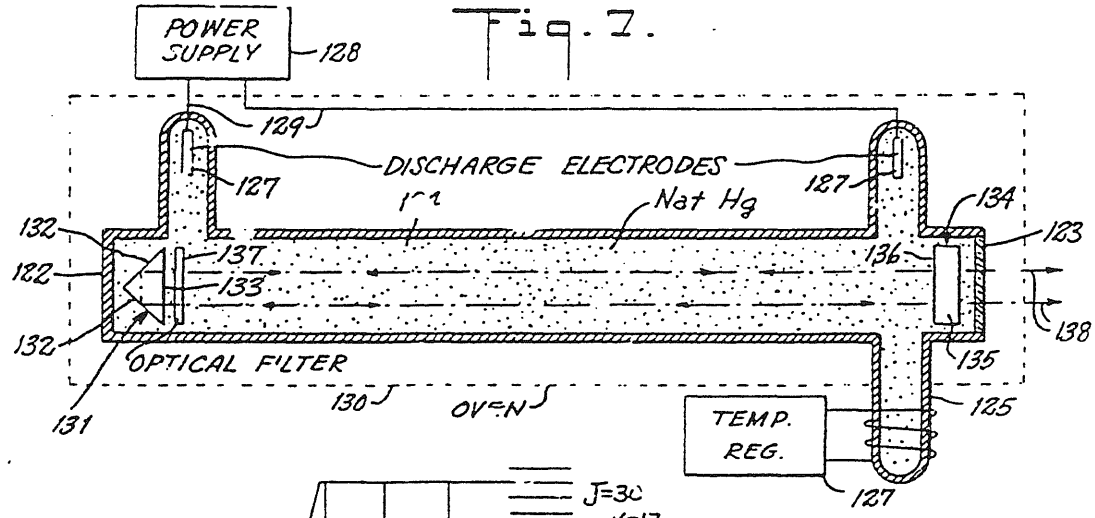
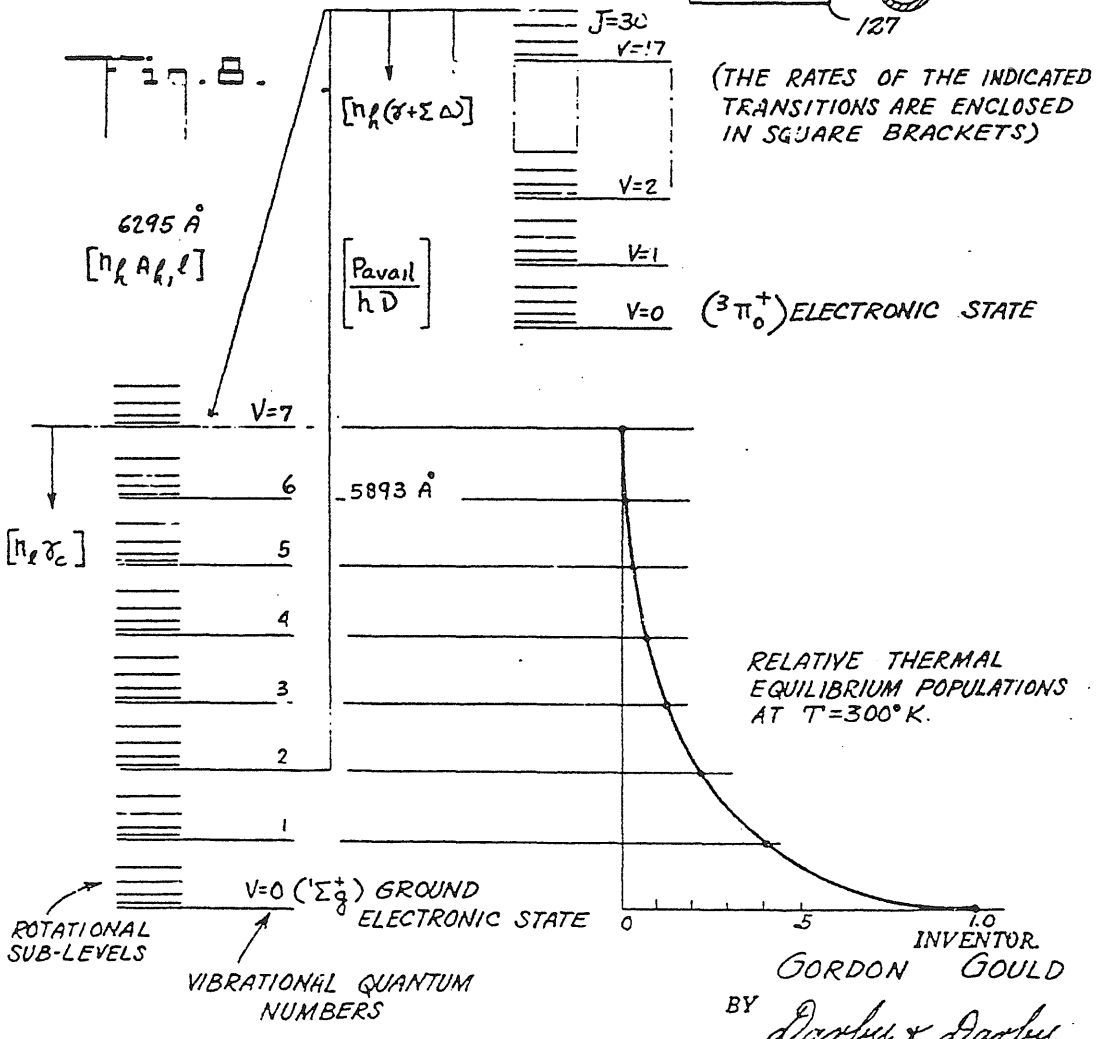


Fig. 8.



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APPARATUS FOR GENERATING RADIATION OF FREQUENCIES HIGHER THAN THOSE OF LIGHT

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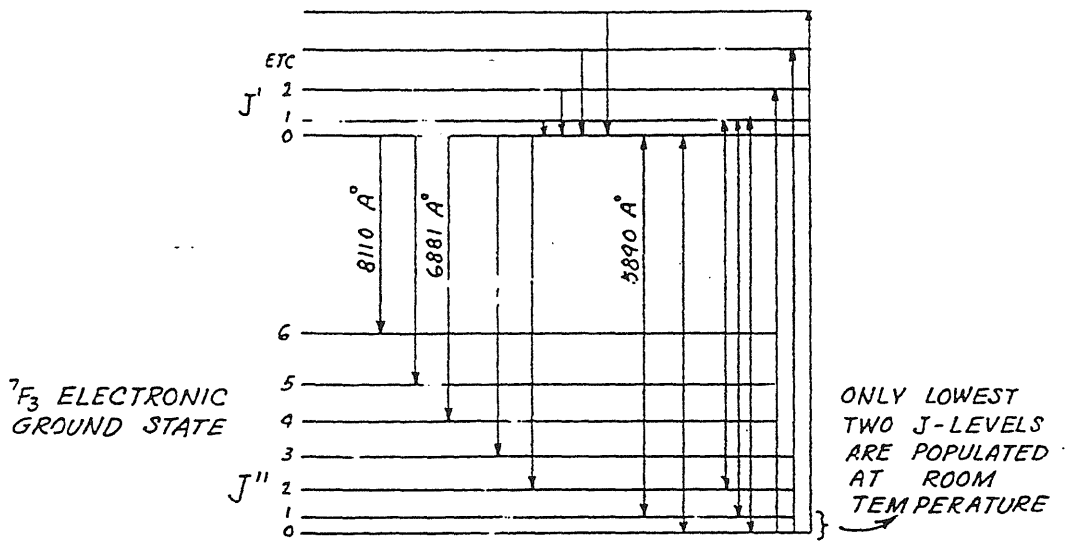
Fig. 9.



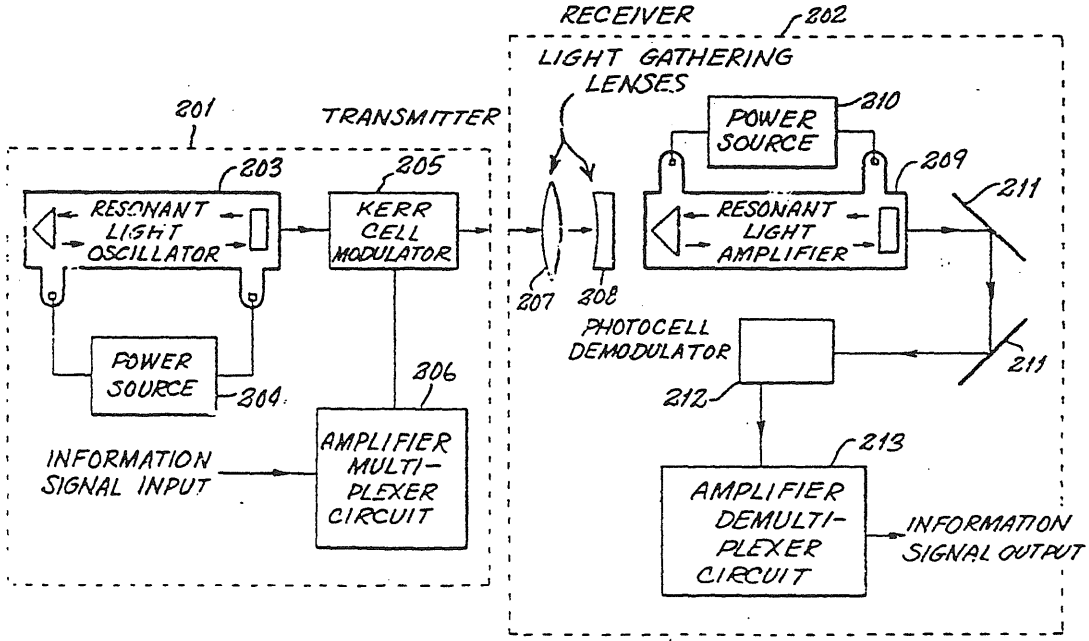


Fig. 10.

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APPARATUS FOR GENERATING RADIATION OF FREQUENCIES HIGHER THAN THOSE OF LIGHT

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Fig. 11.

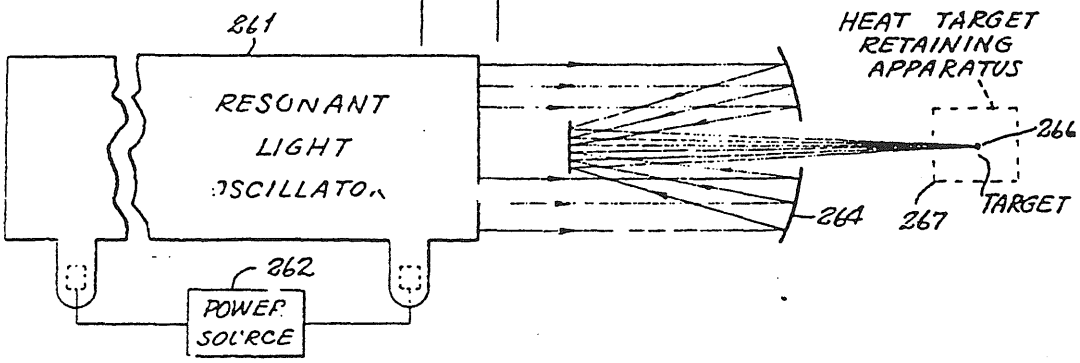


Fig. 12.

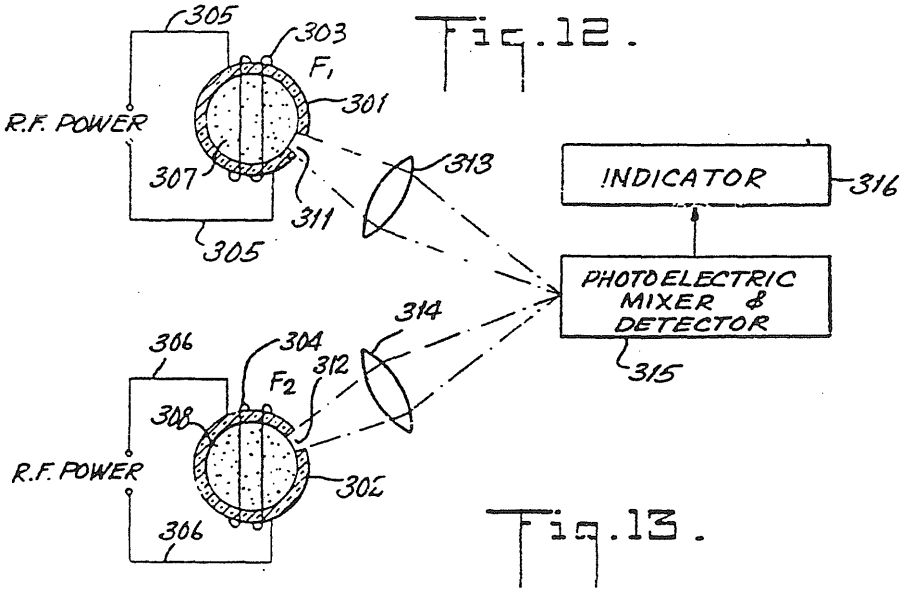
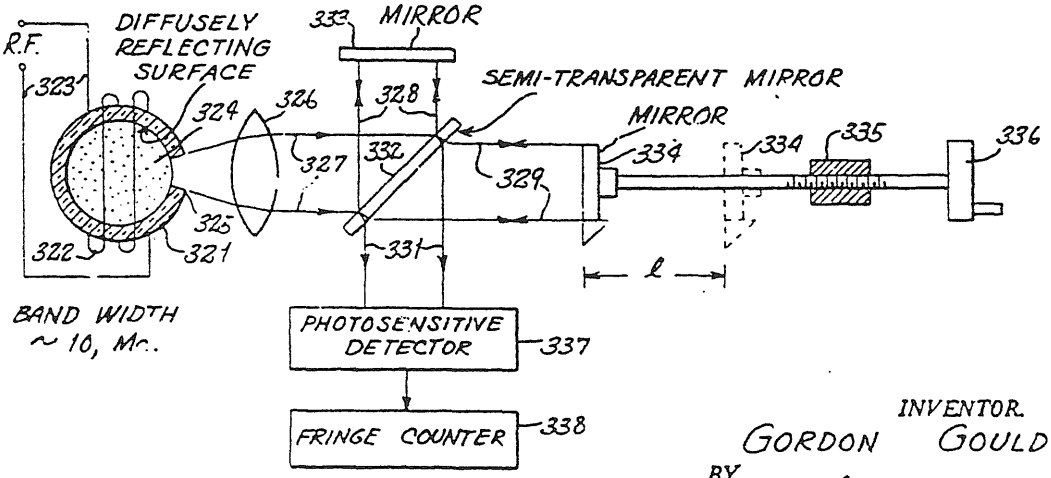


Fig. 13.



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APPARATUS FOR GENERATING RADIATION OF FREQUENCIES HIGHER THAN THOSE OF LIGHT

Filed Aug. 21, 1967 8 Sheets-Sheet 7

Fig. 14.

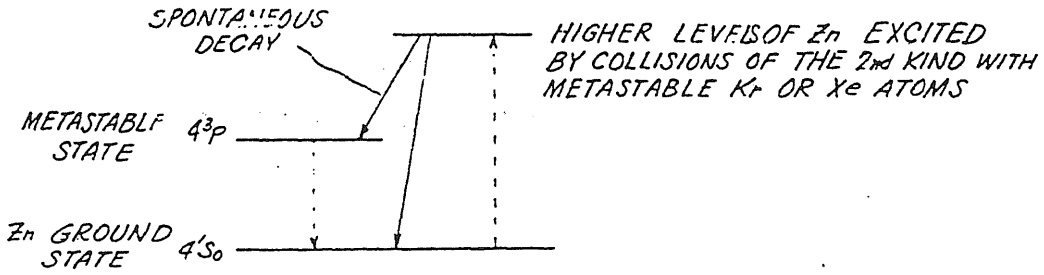


Fig. 15.

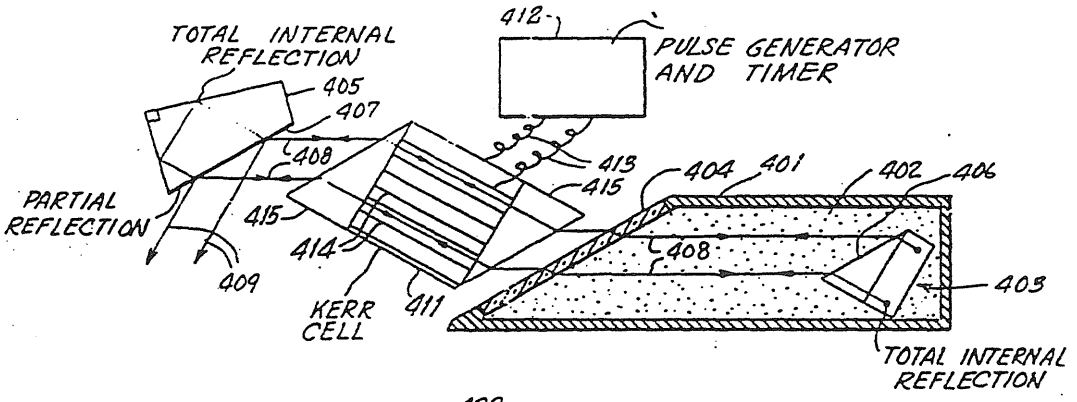
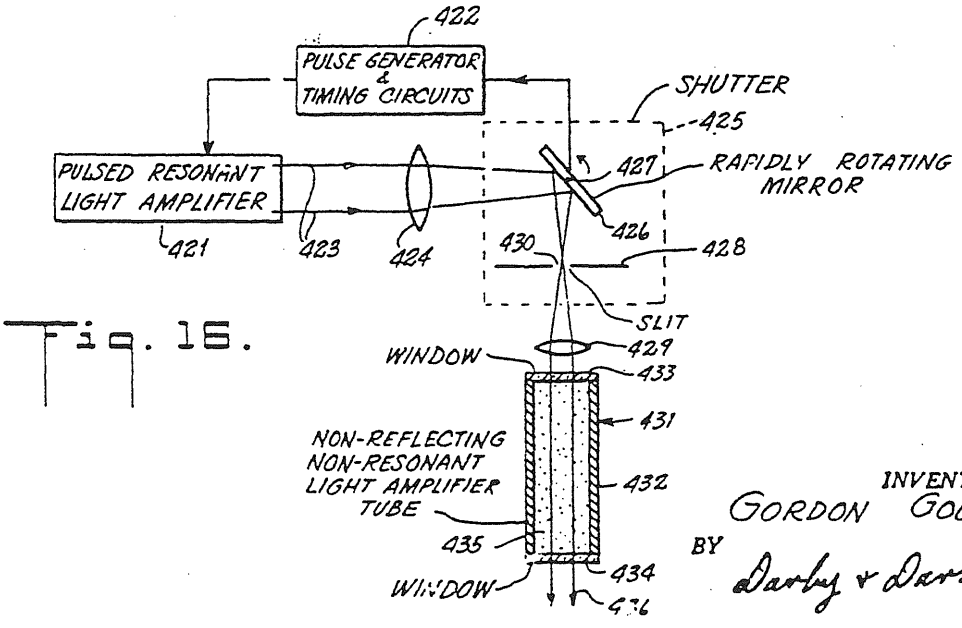


Fig. 16.



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APPARATUS FOR GENERATING RADIATION OF FREQUENCIES HIGHER THAN THOSE OF LIGHT

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Fig. 17.

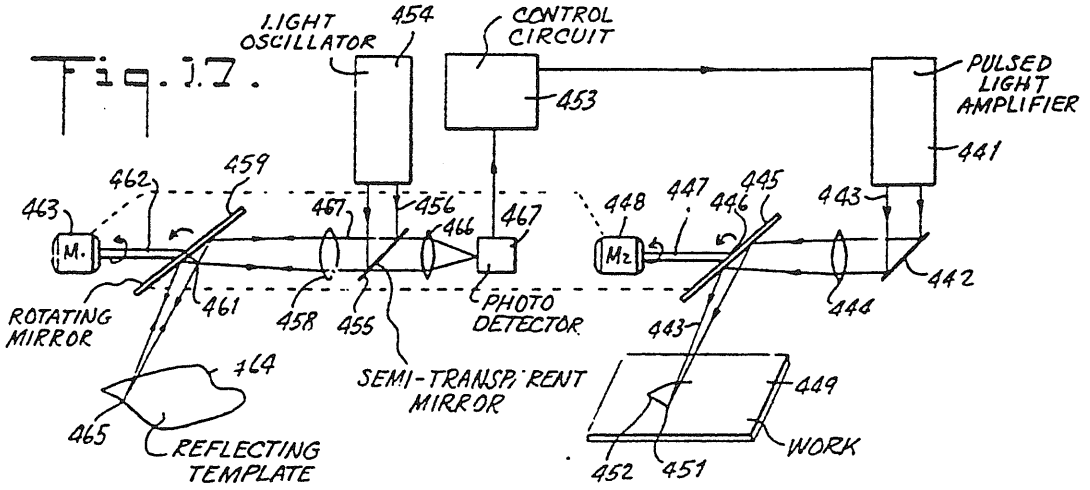


Fig. 18.

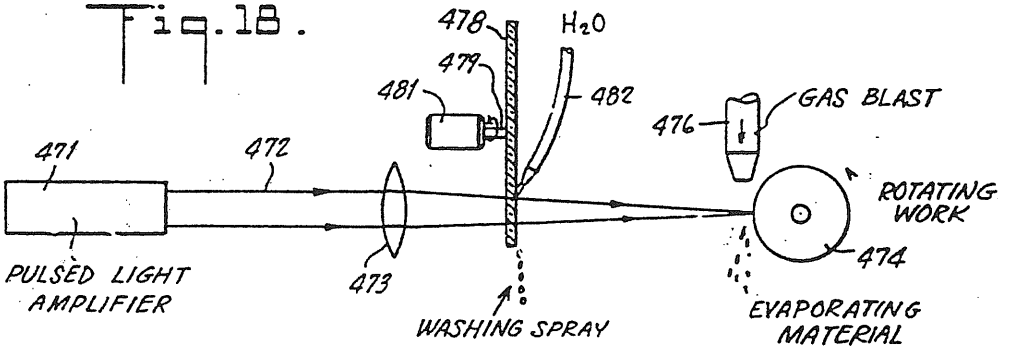
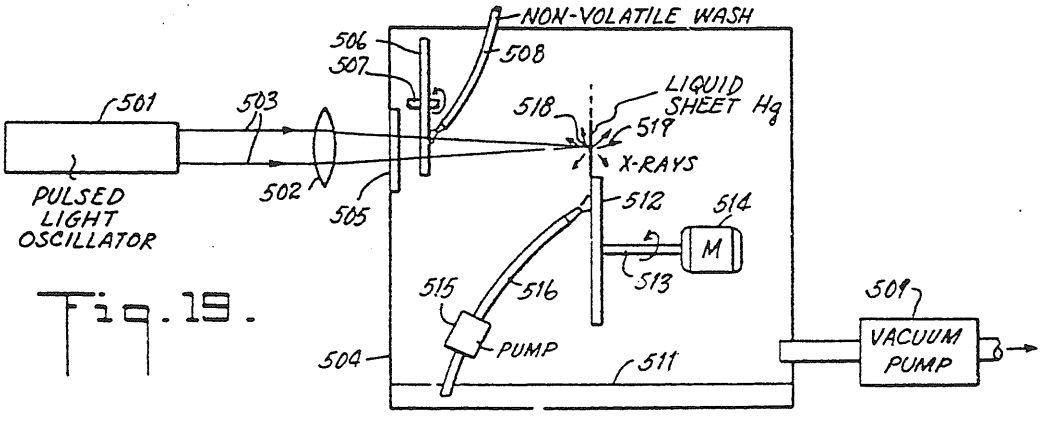


Fig. 19.



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United States Patent Office

3,388,314

Patented June 11, 1968

3,388,314

APPARATUS FOR GENERATING RADIATION OF FREQUENCIES HIGHER THAN THOSE OF LIGHT

Gordon Gould, New York, N.Y., assignor, by mesne assignments, to Control Data Corporation, South Minneapolis, Minn., a corporation of Minnesota

Original application Apr. 6, 1959, Ser. No. 804,540. Divided and this application Aug. 21, 1967, Ser. No. 665,667

3 Claims. (Cl. 321—69)

ABSTRACT OF THE DISCLOSURE

Apparatus of various types is disclosed for the amplification and generation of light by the stimulated emission of photons from ions, atoms and molecules in the gaseous liquid and solid state with the amplified light being characterized by spatial or time coherence, including types of apparatus in which the ions, atoms or molecules are excited by light or by an electronic discharge and types of apparatus in which the stimulated emission of photons is accomplished in a resonator consisting of a pair of opposed specular reflectors or other environment where the light energy is caused to build up in intensity; and systems incorporating such light amplifying or generating apparatus, including systems for the generation of intense heat and high temperature reactions in solids, liquids and gases, communications systems and distance and time measuring systems.

This application is a division of application Ser. No. 804,540, filed Apr. 6, 1959.

The present invention relates to light amplifying devices operating on principles similar to those utilized in a maser (microwave amplification by stimulated emission of radiation) and to various systems incorporating such devices. More particularly, the invention relates to the amplification of light by the stimulated emission of photons from ions, atoms, or molecules in gaseous, liquid or solid state; in particular cases this is accomplished in a "Cavity" or other environment where the light energy will not be free to escape unimpeded, but may be caused to build up in intensity. The amplified light in such apparatus is characterized by spatial or time coherence.

A short explanation of the physical principles involved will be helpful in explaining the nature of the invention.

It is known that atoms, ions or molecules (hereinafter called molecules) ordinarily exist in so-called "stationary" states possessing a more or less well defined energy. While in such a state a molecule does not exhibit an oscillating electric or magnetic moment. However, since a molecule is made up of charged particles, it will be perturbed by any oscillating electric or magnetic field in which it may lie. When so perturbed, a molecule originally known to be definitely in stationary state "*a*" will possess a certain probability of being found in state "*b*" with different energy. When in such a "mixed" state, the molecule may exhibit an oscillating electric or magnetic moment (i.e., it may appear as a system of oscillating charges, or charges in changing orbits). A molecule will undergo a transition from state "*a*" to state "*b*" (i.e., have a large probability of being in state "*b*") if the induced electric or magnetic moment oscillates with almost the same frequency as the applied electric or magnetic field, and if the polarizations and phases of the oscillations correspond. The frequency of the oscillating moment is determined by the Einstein relationship:

$$\Delta E = h\nu_0$$

where:

ν_0=the oscillation frequency

h=Planck's constant

ΔE=the energy difference between the two molecular states.

The same equation $E=h\nu$ gives the energy of the photons associated with the electro-magnetic field. The photon density is proportional to the energy density of the field. During a transition, a photon or "quantum" electromagnetic energy is emitted to or absorbed from the field, depending on whether the molecule is changing from a higher to lower energy state or vice-versa.

Even when there is no radiation energy density of the right frequency directly observable at the molecule, spontaneous transitions occur from higher to lower states with the emission of photons. These transitions are actually induced by random fluctuations in the electro-magnetic field of so-called "empty" space.

The photons emitted during an induced transition have the same phase and polarization as the inducing wave—i.e., they are "coherent" with it. A single atom may radiate a photon in any direction. However many atoms distributed over a finite volume and radiating coherently cooperate to generate a wave having the same propagation vector as the inducing wave, within the limits of a diffraction pattern. That is, they amplify the inducing wave. The radiation from induced emission has a spectral distribution similar to that of the inducing radiation and may be in a very "sharp" line.

Spontaneously emitted photons, because of the random nature of the zero-point fluctuations, have no definite phase or polarization. Because the zero-point fluctuations contain all frequencies, spontaneously emitted radiation has a finite bandwidth, characterized, at the least, by a Lorentzian line shape.

In thermal equilibrium, the populations of two states are related by the Boltzmann distribution factor:

$$\frac{N_{high}}{N_{low}} = e^{-\left[\frac{E_{high}-E_{low}}{KT}\right]}$$

Thus, in equilibrium the population of a higher energy state is less than that of a lower energy state. In particular, the population of a state separated from the lowest by an optical frequency is practically nil at ordinary temperatures. Induced transitions under these conditions necessarily absorb photons from the radiation field.

The foregoing principles can be utilized to devise apparatus for microwave amplification by stimulated emission of radiation which has been termed a maser. If by some means the population of a higher energy state is made larger than that of a lower energy state, induced transitions must necessarily result in the emission of photons to the radiation field. Thus a molecule may emit spontaneously a photon which in turn may induce coherent emissions in neighboring molecules, adding to the total radiation energy. If the transition is at a microwave frequency, the system may be enclosed in a cavity resonant at the same frequency and the escape of the photons prevented. If the power loss from the cavity is less than the power emitted from the molecules, the system will oscillate with a frequency which fluctuates much less than the (Lorentz) bandwidth of the transition. The condition for maser oscillation in a gas is that the excess population density

$$(N_h - N_l) \geq \frac{\hbar}{8\pi^2 p^2 \tau Q}$$

of the gas fills the cavity.

$\tau = T_1 = T_2$ is the relaxation time or state lifetime.

Q≡the "quality factor" of the cavity.

p is the oscillating electric or magnetic moment characterizing the transition.

If the condition for oscillation is not quite met but external power is coupled into the cavity, the "sensitized" or "pumped" molecules will add to or amplify the signal. Because power is lost through the output coupling, the condition for infinite gain, at optimum output, is

$$(N_h - N_l) \geq \frac{h}{4\pi^2 p^2 \tau Q}$$

This amplification adds very little random "noise" to the amplified signal. The minimum noise is determined by thermal fluctuations in the radiation field or by random spontaneous emission, whichever is larger.

Several methods have been proposed for maintaining an excess population in the higher of two molecular energy states of a gas filling a resonant maser cavity. One form of maser which has been proposed achieves "optical pumping" by unpolarized light.

The discussion of this form of "optical pumping" will be given in terms of rubidium (atoms) but would be similar for other cases. Light, characteristic of various spontaneous transitions in Rb, is generated in a discharge lamp and passed through a filter. The filter removes all frequencies except that component line which induces transitions from the $F=1$ hyperfine level of the ground electronic level to some particular higher electronic level. Spontaneous decays back to both hyperfine ground levels will result in a net pumping of Rb atoms from $F=1$ to $F=2$.

To maintain an excess population in $F=2$ over $F=1$, the optical pumping rate need only exceed the collision relaxation rate which may be made as small as 10/sec. Of course this minimum pumping rate would give a correspondingly small power output from the maser.

In the light amplifier, on the other hand, the negligible thermal population of higher electronic states and the high rate of spontaneous emission from these states, make necessary a much higher pumping rate. In general, these effects preclude light amplifier operation between a higher state and a ground state. Usually, a transition between two higher electronic states must be utilized.

Like the maser, the light amplifier will operate on the principle of induced transitions from a higher energy state to a lower energy state with smaller population. However, the techniques usable and possible are appropriate to the optical region of the electro-magnetic spectrum. This frequency range is defined for the present purpose by the limit of transparency of materials in the infrared and ultraviolet to be approximately:

$$10^{-2} \text{ cm.} > \lambda > 10^{-5} \text{ cm.}$$
$$3\times10^{12} \text{ cycles/sec.} < \nu < 3\times10^{15} \text{ cycles/sec. in practice}$$

Another limitation which becomes serious in the far ultraviolet is the amount of power spontaneously emitted by the active atoms. This emitted power increases as ν^4, and must be equaled or exceeded by the input power in order to have light amplification. At $\lambda=1000$ A. an input power of the order of 1 kilowatt is required. Below this wavelength the required input power is too large to dissipate.

Likewise, the useful properties of the light amplifier are qualitatively different from the maser and derive from the vastly shorter wavelength and higher frequency of the radiation involved.

The previous explanation has been given in terms of amplifiers and amplification, but it should be understood that if sufficient gain can be achieved, the light amplifying apparatus can be rendered self-oscillating. Thus a controlled light oscillator may be provided as well as an amplifier. The systems utilizing the apparatus as an oscillator will also be useful.

One form of the light amplifier which will be described as the non-resonant form may be utilized as an oscillator to generate light waves which fall within a narrow frequency bandwidth and have an exceedingly constant average frequency. Light from such an oscillator, particularly when short term frequency perturbations have been

effectively eliminated by averaging over a finite period of time, provides a light frequency standard having an accuracy comparable to the accuracy of any known frequency standards. A light source of this type has obvious applications in the measurement of time, frequency, and particularly of distance by interferometric techniques.

Another form of light amplifier according to the present invention, which will be described as a resonant form, has somewhat different characteristics and is useful for different and quite varied applications. It is a characteristic of a resonant light amplifier constructed according to the present invention that its output is in the form of a beam which is very nearly a plane wave if the input is a plane wave. That is, the divergence of the beam may be very small so the energy of the beam is substantially contained within a very small solid angle of the order of 10^{-8} steradians or less.

Apparatus according to the present invention provides the capability of amplifying light coherently, at least with respect to frequency and phase and in some cases also with respect to direction of propagation, and axis of polarization. Insofar as is known no apparatus with this capability has heretofore been produced.

A coherent infrared light molecular amplifier and generator has been proposed in U.S. Patent No. 2,851,652 to Robert H. Dick. This apparatus and methods proposed by Dicke differ in many respects from those of the present invention. In the Dicke device ammonia molecules are provided in a bounded volume wherein the higher of two molecular energy states is more highly populated than the lower; this is accomplished by physically separating, by electric fields, the molecules in the lower state from a beam of molecules before the beam is permitted to enter the bounded volume. Such activated molecules are capable of amplifying an electro-magnetic wave within a particular frequency range.

The present invention, on the other hand, causes the atoms, ions or molecules of the working medium to be activated to produce the desired population excess in the higher energy level without actual physical separation. Furthermore, the desired population excess is produced within the bounded volume in which emission takes place in the present invention; whereas, in the Dicke apparatus the physical separation to produce the desired population distribution is accomplished outside the cavity after which the working medium is physically transported into the bounded volume in which stimulated emission takes place.

A simple very effective apparatus results from the different method and apparatus for activation utilized in the present invention.

Resonant oscillators according to the present invention have the characteristic of nearly plane wave output. Accordingly, a unique communication system can be provided by the present invention. The capabilities of such a system can be appreciated by the fact that the output light energy may be concentrated within a solid angle of the order of 10^{-8} steradians; this is well within the capabilities of such an oscillator. Such a beam need only be modulated with any information which it is desired to transmit, and detected at the receiving station at a distance (limited by line of sight considerations and atmospheric transmissibility) by conventional photoelectric or other suitable techniques and demodulated. Communication systems utilizing such apparatus would have advantages over virtually all known systems including microwave radio transmission systems and the like, from the point of view of efficiency and amount of information transmitted per channel.

A further system utilizing the principles of the invention makes use of the near planarity of the light wave from a resonant oscillator. When combined with a focusing means such as a parabolic mirror, the resonant oscillator provides a means for concentrating considerable energy in a volume much smaller than had heretofore been possible thus allowing the creation of very high tem-

peratures within a very small volume. In addition to use for scientific research, such a heat source may be used in high temperature processes for industrial purposes and in other applications where exceedingly high temperatures are required.

Although various specific systems incorporating the light amplifier or oscillator have been mentioned above and will be described in more detail, there are numerous other applications of the light amplifying device such as projection TV, high speed photography, precision measurement of length and velocity, illumination, control systems for various kinds of equipment, generation of X-rays, etc. In addition to the above objects and advantages of the present invention, it is an object of the present invention to provide a light amplifier wherein light is amplified by raising atoms, ions or molecules to a particular energy level and stimulating them by exposure to light having a frequency corresponding to the energy difference between that level and a lower energy state of the atoms, ions and molecules thus stimulating the atoms, ions or molecules to decay to the lower energy state with the emission of light energy coherent with the stimulating light, thereby amplifying it.

It is another object of the present invention to provide such a light amplifier wherein a confined space is provided with reflecting walls causing emitted light to re-traverse said space repeatedly causing additional stimulation of atoms, ions or molecules within said space.

It is still another object of the present invention to provide such a light amplifier utilizing specular reflectors spaced so that the paths therebetween are of a definite distance representing a definite number of wavelengths of the amplified light whereby other wavelengths are discriminated against and whereby a nearly planar wave of light is generated.

It is still another object of the present invention to provide such a light amplifier wherein the conditions for oscillation may suddenly be changed, thereby causing the excited atoms, ions or molecules to emit photons in a short, transient wave-train or light pulse of greater peak power than may be generated in steady-state operation.

It is a further object of the present invention to provide such a light amplifier wherein the atoms, ions or molecules are raised by exposure to light from a gaseous discharge lamp to a particular desired energy level (from which stimulated decay is to be produced).

It is a still further object of the present invention to provide a light amplifier of the type described immediately above in which the gaseous discharge lamp is filled with an element different from that of the atoms, ions or molecules to be excited and which has an atomic resonance which by change coincides with a spectrum line of the atoms, ions or molecules to be excited.

It is a still further object of the present invention to provide such a light amplifier wherein the atoms, ions or molecules are raised to a particular desired energy level (from which stimulated decay to a lower level is to be produced) by supplying electrical energy to produce a discharge within the confined space in which the atoms, ions or molecules to be excited are contained.

It is a still further object of the present invention to provide such a light amplifier wherein the atoms, ions or molecules are raised to a particular desired energy level (from which stimulated decay to a lower level is to be produced) by utilizing collisions of the second kind with atoms, ions or molecules of a different element or elements from that to be stimulated to produce the emission of light.

It is a still further object of the present invention to provide a light amplifier having an optical system with reflecting elements having surfaces subtending predetermined angles by which light from a range of angles is accurately reflected back upon itself in a manner analogous to the operation of a microwave corner reflector.

It is an additional object of the present invention to provide such a light amplifier having an optical system consisting of filters and reflectors which will permit the generation light only within a predetermined frequency range and with a definite polarization.

Other objects and advantages will be apparent from a consideration of the following description in conjunction with the appended drawings, in which:

FIG. 1 is a partially schematic illustration in cross-section of a nonresonant light amplifier designed to be excited by an external source of light radiation;

FIG. 2 is a Grotrian diagram of energy levels of sodium presented to aid in the explanation of light amplifying apparatus according to the present invention;

FIG. 3 is a partially schematic illustration in cross section of a nonresonant light amplifier designed to be excited by an electrical discharge within the amplifier cavity;

FIG. 4 is a partially schematic illustration of a resonant light amplifier excited by incoherent light radiation and utilizing triangular prisms as reflecting surfaces;

FIG. 5 is a partially schematic illustration in cross-section of an alternative optical system for the apparatus of FIG. 4, for example, in which only light polarized in the plane of the paper will be generated;

FIG. 6 is a partially schematic illustration in cross-section of a resonant light amplifier excited by incoherent light radiation and utilizing optically flat parallel mirrors for its reflecting surfaces;

FIG. 7 is a partially schematic illustration in cross-section of a resonant light amplifier designed to be excited by a discharge within the resonant cavity;

FIG. 8 is a diagram of the energy levels of the iodine molecule useful in explaining a form of the invention utilizing coincidence of spectral lines in energizing a working medium in a light amplifier;

FIGURE 9 is a diagram of the energy levels of the Europium ion, Eu^{+++}, useful in describing a form of the invention utilizing a non-gaseous working medium;

FIG. 10 is a schematic diagram of a communication system incorporating resonant light amplifiers and oscillators;

FIG. 11 is a schematic diagram of a high temperature heating apparatus utilizing a resonant light oscillator according the present invention;

FIG. 12 is a schematic diagram of a frequency standard employing nonresonant light oscillators according to the present invention;

FIG. 13 is a schematic diagram of interferometric apparatus comprising a nonresonant light oscillator according to the present invention;

FIG. 14 is a diagram of some energy levels of zinc useful in describing a form of the invention utilizing an internal discharge for exciting the working medium;

FIG. 15 is a partially schematic illustration in cross-section of a form of resonant light amplifier wherein the light path traverses a Kerr cell by means of which the losses of the system may be rapidly varied in order to generate a transient light pulse.

FIG. 16 is a partially schematic diagram of a system for generating short light pulses comprising a pulsed resonant light amplifier of the type shown in FIG. 15, for example, a rapid shutter for "trimming" the ends of the transient wave-train, and a nonresonant light amplifying tube which further shortens and "peaks" the pulse;

FIG. 17 is a partially schematic diagram of a system wherein the light beam from a resonant light amplifier is manipulated by mirrors to scan an object and by detection of the reflection therefrom to provide information for the automatic control of equipment which may comprise a pulsed light amplifier and moving mirrors;

FIG. 18 is a partially schematic diagram of an evaporative machining apparatus utilizing a light oscillator according to the present invention; and

FIG. 19 is a partially schematic diagram of apparatus for subjecting a liquid to a very high temperature and

utilizing a light oscillator according to the present invention.

Nonresonant light amplifier

Referring to FIG. 1, there is shown at 11 a spherical cavity 11 forming a principal part of a nonresonant light amplifier. Although a spherical cavity has an optimum volume to surface ratio, the cavity need not be of this shape but could be cylindrical, rectilinear, or of other shape if desired.

The cavity 11 is provided with apertures 12 and 13 for the output and the exciting light input respectively for the cavity. Suitable windows 14 and 15 are provided to cover the apertures 12 and 13 and should be made of a material such as glass or the like, having a high transmission coefficient for the frequency of light involved.

The interior 16 of the cavity 11 is filled with a sensitized working medium in this form of the invention, the nature and function of which will be hereinafter explained in more detail.

The wall 17 of the cavity 11 is rendered reflective as by a reflective coating 20. This surface may either be a specular reflector such as polished metal, or a diffuse reflector. For light in the visible region the highest reflectivity is achieved with a diffuse reflector such as magnesium oxide powder, and such a reflective surface would generally be preferred for the reflecting coating 20.

A gaseous atmosphere for the cavity interior 16 is supplied from a reservoir 18 connected to the cavity by a conduit 19.

A heating coil 21 controlled by a temperature regulator 22 may be utilized to maintain the vapor in the interior of the cavity at the desired pressure. A temperature control oven 23 is provided surrounding the cavity 11 to mantain the cavity at a temperature higher than that of the reservoir 18 thus preventing condensation in the cavity 11 and assuring control of pressure by means of a temperature regulator 22 regardless of changes in ambient temperature of the cavity.

Light is directed from an exciting light source 24 through the window 15 to the interior of the cavity 11. In a typical case, the light source 24 will comprise a gas discharge lamp having a gaseous atmosphere similar in composition to that of the atmosphere in the interior 16 of the cavity 11.

Although solid or liquid fluorescent material may be advantageous in certain applications rather than a gaseous medium within the cavity 11 in FIG. 1, transition processes in gases are more completely understood and accordingly the explanation will be primarily directed to this more readily understood form.

Operation of nonresonant light amplifier

The operation of the light amplifier of FIG. 1 will first be explained with reference to a relatively simple form of excitation, that is, excitation by resonance radiation. It should be understood that other forms of excitation which will later be explained may in many cases be preferable to the simpler type of excitation by resonance radiation.

A desirable medium for this form of excitation is sodium vapor and for the purpose of this explanation, it will be assumed that the interior 16 of the cavity is filled with sodium vapor and that the exciting light source 24 is a sodium vapor lamp.

FIG. 2 is a diagram of some of the higher electronic levels of sodium. The hyperfine structures of these electronic levels are not shown.

The free-space wavelengths (in Angstroms) of the electro-magnetic radiation emitted during transitions between certain pairs of levels are given on the diagram of FIG. 2. The measured or estimated spontaneous emission rates for these transistions are also indicated. Electric dipole radiation selection rules permit transistions only between levels in adjacent columns of the diagram. Thus no transitions occur between levels with the same letter designation (same orbital angular momentum). Atoms in the ground level ($3^2S_{1/2}$) can be excited by resonance radiation from a sodium lamp only to the various P-levels. However, all states may be excited by collisions with energetic electrons in a discharge or by collisions with other excited atoms (collisions of the second kind).

It is desired to achieve a higher population in some higher level than in a lower level, to which transitions may be induced by the presence of light energy of suitable frequency. If it is assumed that only the 6^2P levels are excited directly from the ground level, light exciting other levels could be removed by an appropriate optical filter. Then by spontaneous emission various lower levels will become populated to some extent. The populations in dynamic equilibrium may be calculated from the spontaneous decay rates.

If the 6^2P levels are assumed to have a unit population, the computed populations of the other lower levels are shown in the diagram. It may be noted that the population of the $4^2S_{1/2}$ level is only 0.0067 of the 6^2P levels population and hence transistions generating the 8660 A. infrared line may be expected in a suitable enclosure.

From the diagram of FIG. 2 and the foregoing explanation, it will be seen that when the medium in the cavity 11 is excited by the light from the light source 24, a condition is produced where the population of a higher energy level (6^2P) is much higher than the population of a lower energy level ($4^2S_{1/2}$) so that the presence of light of the frequency represented by the difference between these two energy levels (wavelength 8660 Angstroms) will stimulate decay from the higher energy level to the lower energy level with the emission of more light of this same frequency.

Accordingly, when the pumping rate due to excitation from the source 24 is sufficiently great to maintain a large population difference between these two levels in favor of the higher level, and when losses in the cavity are reduced to a sufficiently low level as by maximizing the reflectivity of the surface 20, conditions for sustained oscillation will be met and the apparatus of FIG. 1 will operate as a nonresonant light oscillator.

Obviously, if the conditions for oscillations are approached but are not met, light of the appropriate frequency (8660 Angstroms) introduced into the cavity will be amplified by the stimulated emission of radiations and the output of the cavity at that frequency will be greater than the input thus providing amplification, but self-sustained oscillation will not occur.

The nonresonant light amplifier of FIG. 1 is schematically shown with a relatively small window for the introduction of light excitation; in practice, it will generally be desirable to utilize a substantial portion of the surface of the cavity as a window for light excitation. It will be recognized that increasing window area cuts down on the available surface for reflection. The effective reflection coefficient may be kept relatively high by arranging the reflective portions of the cavity on opposite portions of the surface of the amplifier enclosure.

If the window area desired for light excitation is a substantial portion of the total area of the cavity, it may be preferred to make the amplifier in another form, such as cylindrical, for example. This form may be particularly desirable as the curved peripheral surface of the cylinder may be made transparent for the introduction of light excitation while the ends of the cylinder may be rendered diffusely reflective. With this arrangement a large amount of light power may conveniently be transmitted into the cavity. Although there may be some reduction of average effective reflection coefficient, this is offset by other considerations.

If the cylindrical nonresonant amplifier described above is made in elongated form, only light within a narrow angular range of direction of propagation will be amplified and thus the noise due to spontaneous emission will be reduced, yielding a narrower output bandwidth. The

output of an elongated cylindrical nonresonant amplifier may largely be restricted to an angle on the order of approximately 6°; this is much more convenient and may be directed more efficiently than the diffuse output as from a spherical amplifier or oscillator.

Tendency toward resonance in the elongated cylindrical nonresonant light amplifier will be avoided by the fact that light paths of many different lengths will exist between the reflectors; if desired, the reflectors may be shaped to increase the diversity of optical path lengths between reflectors.

Various elements other than sodium may be utilized in the construction of such a nonresonant amplifier, particularly those elements in group 1 of group 3. The characteristics of sodium, however, are generally more favorable than those of other elements.

A slightly more complex mode of operation has definite advantages over the relatively simple resonance radiation excitation described above. This mode of operation utilizes enhancement of intensity by collisions of the second kind to enhance the intensity of a particular spectral line from the lamp.

Considerable study has been made of the phenomenon of "sensitized fluorescence." Atoms of one kind, excited to a particular electronic level, may, on collision with atoms of a second kind, transfer their excitation energy. It has been shown experimentally and theoretically that the transfer process is most probable if two conditions are fulfilled:

(a) The smaller the energy difference between the levels of interest in the two kinds of atoms, the greater is the collision cross-section for the exchange.

(b) The total electronic angular momentum of the two atoms remains the same before and after the collision (Wigner partial selection rule).

In connection with rule (a), the energy difference must be converted to or from kinetic energy of the atoms. If the energy difference is less than "thermal energy" ($<KT\approx 0.03$ ev.) and if rule (b) is obeyed, the cross-section may be more than 100 times the "kinetic theory" cross-section. In particular, collisions of the second kind have been observed between metastable Hg (6^3P_0) atoms and sodium atoms in a mixed gas. It will be observed from the diagram of FIG. 2 that the Hg (6^3P_0) level falls between the Na (7S) and Na (6P) levels and is <0.045 ev. from either. It has been observed that the visible Na (7S→3P) 4751 A. line became as intense as the Na (3P→3S) 5893 A. line under certain conditions, showing that the bulk of the energy was transferred to the Na (7S) level. The intensity enhancement will be about 20 times. It may be expected that transitions from the $6P_{1/2}$ level will be similarly enhanced.

The proper mixture of Hg in Na amalgam to obtain the necessary pressure of both Na ($\sim 10^{-4}$ mm. Hg) and Hg (~ 1.0 mm. Hg) at operating temperature can be obtained from published data or approximately from Raoult's law.

From the foregoing explanation, it will be seen that by utilization of collisions of the second kind with a different kind of atom, the efficiency of the operation by which a greater population of a higher energy level is produced by optical-pumping may be substantially increased with a resulting increase in efficiency of operation of the light amplifying device.

Nonresonant light amplifier with internal discharge

FIG. 3 shows a modification of the nonresonant light amplifier in which the gaseous medium within the cavity is excited directly by application of radio frequency energy rather than being excited by a light source as in FIG. 1 (low frequency energy or a direct current discharge could be used instead where desired).

A cavity 31 is provided having an opening 32 for the transfer of light output to the exterior of the cavity. A rod of transparent material shown at 34 may be utilized to transmit the light output from the apparatus, or alternatively, windows may be used as illustrated in FIG. 1.

The interior 36 of the cavity is preferably filled with a gaseous medium such as a mixture of mercury and sodium vapors as previously described. The wall 37 of cavity 31 is provided with a reflecting surface 40 such as magnesium oxide.

A reservoir 38 is connected by a conduit 39 to the interior 36 of the cavity 31 in order to provide a gaseous atmosphere of the desired composition and pressure within the cavity 31. A heater 41 is provided for the reservoir 38 and is controlled by a temperature regulator 42 thus providing control of the pressure of the vapors within the cavity. Excessive fluctuation of pressure within the cavity 31 and condensation within the cavity 31 is prevented by maintaining the cavity 31 in a temperature controlled oven 43.

Energy is supplied to excite the atoms within the cavity 31 by a coil 44 surrounding the cavity and supplied with high frequency excitation which may be of a frequency of approximately 100 megacycles for example.

Thus in the device of FIG. 3 excitation of atoms within cavity 31 is by a radio frequency energy induced discharge rather than by light excitation as in the apparatus of FIG. 1. In other respects the operation of the apparatus of FIG. 3 is substantially similar to that of FIG. 1.

Obviously the discharge within the cavity 31 may be produced in other manners such as by a direct current or low frequency discharge between electrodes within the cavity or by capacitively coupling high frequency electrical energy into the cavity rather than using the inductive coupling illustrated in FIG. 3.

The advantage of producing a discharge within the cavity rather than depending upon absorption of energy from a light source is readily understandable when it is realized that only approximately 20% or less of the light energy directed into the cavity is absorbed to produce useful pumping action. Furthermore, only a limited amount of "pumping" light can be introduced through a small hole. As the hole is made larger, the loss of light from the cavity becomes substantial. Where the discharge is produced within the cavity to excite the atoms, substantially all of the energy introduced into the cavity is absorbed in the working medium and a large fraction converted to useful output. If an internal discharge is used to excite the atoms, a large amount of "pumping" power may be coupled into the cavity.

The usefulness of the nonresonant light amplifier is somewhat limited by the large amount of noise present in the output signal. Random fluctuations in frequency or phase of the signal are generated by spontaneous transitions. In particular the usefulness of the nonresonant apparatus as an amplifier (as contrasted with an oscillator) is limited by this background of random spontaneous emission giving rise to a noise bandwidth of approximately 1000 megacycles (the Doppler width of the spectral line). The approximate equivalent noise temperature of the nonresonant light amplifier at the center of the visible spectrum is 30,000° K.

On the other hand, the nonresonant light amplifier, operating as an oscillator, emits an optical line up to 50 times narrower and 3,000 times as intense as the weak spontaneous emission background on which it is superimposed.

Furthermore, the nonresonant light amplifier, in spite of short term fluctuations in frequency, has a long term average frequency which is very constant. Thus by averaging the frequency over a finite period of time a light frequency standard may be obtained having a degree of accuracy comparable with that of any known frequency standard. Such a standard is useful not only in the measurement of time but also in the measurement of distance by interferometric techniques as will be understood by the description of systems for these purposes described hereinafter.

Resonant light amplifier

The previously described light amplifier(s) of FIGS. 1 and 3 are termed a nonresonant light amplifier(s) because the frequency of the light output, while relatively constant, is not to any substantial extent dependent upon the dimensions of the cavity within which the oscillation is generated.

An alternative form of the light amplifier will now be described in which the "resonant" frequency of the device is highly dependent upon the dimensions of the cavity. The resonant light amplifier also differs in other important respects, but the resonant characteristic of the device is utilized as a convenient way of distinguishing it from the previously described nonresonant light amplifier.

In FIG. 4 there is shown an elongated cavity 51 enclosed at the ends by end portions 52 and 53. As was the case with the nonresonant apparatus, a reservoir 54 is provided for supplying a gaseous atmosphere to the interior of the cavity. A heater 55 illustrated as a heating coil is controlled by a temperature regulator 56 to insure control of the pressure within the cavity 51.

As in the case of the light amplifiers of FIGS. 1 and 3, an oven 57 may be provided to enclose a portion of the apparatus to maintain it at a temperature higher than that of the reservoir 54 thus preventing condensation within the cavity 51 and allowing closer control of the pressure of a gaseous atmosphere.

From the foregoing explanation, it will be seen that the interior 58 of the cavity 51 is, in this form of the invention, supplied with a gaseous medium, the pressure of which can be controlled by means of the temperature regulator 56. The gaseous medium within the cavity 51 in FIG. 4 will be considered to be sodium, although as previously explained, other mediums may be used.

Excitation for the medium within the cavity 51 is provided by a cylindrical gas discharge lamp 59 surrounding the cavity 51. The gas discharge lamp 59 is preferably a sodium vapor lamp filled with a suitable gas or a combination of gases such as sodium and argon.

The outer wall 61 of the lamp 59 may be provided with a reflecting surface such as magnesium oxide to conserve light, whereas the inner wall 62 of the lamp 59 is preferably highly transparent to the desired spectral components of the light produced by the lamp.

The wall of the cavity 51 is also preferably highly transparent to this light. It is obvious that if desired a single wall may be provided between the interior 60 of the lamp 59 and the interior 58 of the cavity 51, thus making these two portions of the device as one integral element. The wall 62 may be formed of a material acting as an optical filter, if desired, thus discriminating against certain components of the light from lamp 59 which are not desired. The lamp 59 may also be provided with a reservoir 63, a heater 64 and a temperature regulator 65 in a manner similar to that provided for the cavity 51 so that the pressure within the discharge lamp may be independently controlled by means of the temperature regulator 65. It will be noted that the oven 57 also maintains the interior of the discharge lamp 59 at a higher temperature than that of the reservoir 63.

Electrodes 66 are provided in the lamp 59 and are supplied by power from a supply 67 through leads 68. The nature of the electrical excitation of the lamp 59 may be selected for the best results in a particular application and may be, for example, direct current, alternating current, or high frequency radio frequency excitation, etc.

It has previously been noted that it is desirable to provide means to confine and retain the light energy within the cavity in order that a number of emissions of light energy will be stimulated and the intensity of the light will be built up providing amplification in a manner somewhat analogous to that which occurs in an electron multiplier tube through avalanche effect.

The apparatus of FIG. 4 differs from the previously described nonresonant light amplifiers of FIGS. 1 and 3 in that the reflectors are specular reflectors rather than diffuse reflectors as used in the nonresonant cavity.

The reflectors in the cavity 51 comprise prisms 69 and 71. Mirrors may be used as reflectors in the cavity 51 but in many instances prisms are preferable due to the requirement for an extraordinary high degree of planarity and parallelism when plane mirrors are used and which requirement is significantly reduced by the use of prisms.

Thus the use of prisms is a feature of the invention of great practical importance. Prisms 69 and 71 are illustrated as triangular right-angled prisms. That is, the faces 73 of prism 71 are at right angles to each other as are the faces 72 of prism 69 (one of the faces 72 is not visible due to the orientation of a prism 69). Such 90° prisms can be ground with a high degree of accuracy. Assuming that the prisms are so ground, it is known that light rays entering the faces 75 or 74 of the prisms 71 and 69, respectively, are returned almost exactly in the direction from which they originated for a substantial range of angles of incidence with the front face (75 of the prism 71, for example). Furthermore, the effective pathlength for rays entering the face 75 is substantially the same over the surface of the face even though the angle at which the rays strike the face 75 is not exactly 90°.

The prisms 69 and 71 are preferably oriented so that their rear (roof) edges joining the diagonal faces are at 90°. That is, in FIG. 4 the edges joining the reflecting faces of the prism 69 are vertical while the edges joining the reflecting faces of prism 71 are horizontal.

Accordingly, with face 75 nearly perpendicular to the direction of impinging light rays, the prism 71 may be rotated several degrees about a horizontal axis extending into the paper without causing an appreciable change in the direction of reflection. The prism 69 can be rotated several degrees about a vertical axis without causing an appreciable change in the direction of the reflected rays. As a result, the placement of the two prisms 69 and 71 is not critical with respect to rotation about either of the orthogonal axes parallel to the rear edges of the prisms. As a result, the prisms 69 and 71 once ground to the tolerance required as regards the planarity and angular relationship of the various faces can be placed within the cavity 51 without any highly critical requirements of parallelism as regards the faces 74 and 75.

There are several alternative ways to reduce the criticality of the angular positioning of the reflectors. For example, one may replace the prism 71 with a corner reflector with three mutually perpendicular planar surfaces (which may also be a prism) and replace the prism 69 with a plane mirror. The mirror may be a "low loss" multilayer reflector which selectively reflects only light of the desired wavelength.

The advantage of utilizing prisms rather than mirrors may be appreciated by consideration of the general mode of operation of the resonant light amplifier. It is desired that the light rays traverse the distance back and forth between the reflecting beams a considerable number of times. If the optical pathlength over each circuit of the two reflecting means, and in fact, if the path circuit over a plurality of circuits of the reflecting means is not the same for each and every portion of the reflecting surface within the accuracy of a fraction of the wavelength, interference will be produced and a resonant nature of the system will be diminished or destroyed.

It is likely that one limit of the efficiency of the system will be the tolerances to which flat optical surfaces may be produced. It may be impossible to obtain a surface with a closer tolerance of flatness than approximately one-fiftieth of a wavelength as a practical matter. This, of course, will limit the efficiency of resonant light amplifiers utilizing prisms as well as the resonant light amplifier utilizing flat mirrors. In the case of the mirrors, however, it would also be necessary to place and retain the mirrors in respective ends of the cavity (which may be separated in a typical case by 30 centimeters) in parallel

relationship with a tolerance of one-fiftieth of a wavelength, approximately. This can likely be achieved although it would necessarily involve a phenomenal degree of precision and expensive techniques that would go with such a precise operation. Furthermore, the completed device would be highly sensitive to disturbances and vibration of all types including physical accelerations, changes in temperature, etc.

The prisms 69 and 71 are preferably provided with non-reflective coating on their front faces 74 and 75, as light reflected from these faces will generally be lost due to being out of phase or slightly misdirected and will not add coherently to the main standing wave in the cavity.

The faces 73 of the prism 71 would normally be substantially 100% reflective. An output from the cavity (or in the case of an amplifier operation, an input as well) may be provided through one or both of the faces 72 of the prism 69. The face 72 may be rendered partially transmissive by placing on or near the face a material which has an index of refraction which does not differ from the index of refraction of the prism sufficiently to provide total internal reflection. By this means, any desired portion of the light impinging on one or both faces 72 may be transmitted to the outside of the cavity. Conversely, if the apparatus is to be used as an amplifier, thus necessitating an input, the same path or a similar path may be used for the input to the light amplifier.

In the case of an amplification operation as contrasted to an oscillator operation, there will generally be a loss of energy involved in transmitting the input signal into the cavity and transmitting the output signal out of the cavity. Obviously any normal type of transmission path for light energy into the cavity will also provide a path for the same kind of light energy out of the cavity. One may expect a loss on the order of 50% in this operation, but this will not be serious in view of the overall gain produced by the light amplifier. Such a problem need not arise in the case of a light oscillator as no input signal is required due to the fact that oscillations are built up from ever-present random fluctuations as is the case with other types of oscillator devices.

Operation of resonant light amplifier

As previously explained, the induced emission from atoms is coherent with the inducing radiation. That is, it has the same phase, frequency and polarization. If many atoms over the breadth of the inducing wave are emitting, the emitted radiation will also be a substantially plane wave with the same propagation vector except for small diffraction effects. With this understanding it will be seen that the resonant light amplifier of FIG. 4, although it has only small reflecting surfaces compared with its total cavity internal area, effectively confines the amplifying operation due to the fact that only light energy within a very narrow range of frequency and propagation direction is amplified and this energy has a direction of propagation vector such that it is substantially contained between the two reflecting surfaces.

There will be slight losses of energy off the edge of the reflectors due to slight discrepancies in the angle of propagation of the rays being amplified. This slight energy loss will not be sufficient in a well designed apparatus to prevent proper operation of the device.

Within its frequency an angular limits, determined by the dimensions and loss coefficient on reflection, the resonant light amplifier will amplify plane waves continuously variable in direction and frequency.

If the input wave is plane, the output wave is almost but not exactly plane. The finite size of a wavelength, λ, allows the wave front to spread as it travels. At great distances from a circular end-plate, the wave front, instead of remaining a circle of constant diameter, exhibits the Fraunhofer diffraction pattern of intensities. In this pattern approximately 98% of the light falls in a central spot of angular radius

$$\Delta\theta = 1.220\frac{\lambda}{2R}$$

more than half the light falls in a cone of half this angular radius. If the wave is focused on a nearby plane, one observes the same pattern instead of a point. The Rayleigh criterion for angular resolution of two plane waves focused in a telescope is that the waves shall make an angle with each other equal to $\Delta\theta$. That is, the maximum of one falls on the first dark ring of the other pattern. Thus plane waves from different points of a distant object could be amplified coherently by the resonant light amplifier and then focused on a screen or the face of a television camera tube. The resulting image could be scanned or otherwise used.

If a plane wave passes through a circular aperture, then at nearby distances the wave starts to spread and forms the Fresnel diffraction pattern.

Thus as a "plane" wave reflects back and forth inside the tube, light dribbles out of the cylindrical space between the reflectors. The fraction of light lost by this mechanism in travelling a distance $L=L/a$ is very approximately given by

$$\phi_{\text{Diff.}} = \text{fract. lost} = \frac{1}{2R}\sqrt{\frac{L}{2a}}$$

where L/a is the mean distance travelled by a photon before it is lost at a reflector.

If $\phi \rightarrow 1$ then the effective loss on reflection, a, will be appreciably increased. This puts a lower limit on the radius of the reflector. If

$L=100$ cm.
$\lambda=5\times10^{-5}$ cm.
$a=.05$
$2R=1$ cm.

then ϕDiff.$\approx$0.3 which is about as high as desirable.

Amplifier with brewster angle prisms

Another form of resonant light amplifier is shown in FIG. 5, comprising a cavity 81 filled with a working medium 82, of any of the types described herein.

A prism 83 is provided in the cavity 81. This prism comprises two portions, 83*a* and 83*b*.

The portion 83*a* of prism 83 is a 90° triangular prism, the triangular faces of which are not visible in FIG. 5. One reflecting face 84 of the prism 83 is shown in FIG. 5; the other reflecting face is on the reverse side of the prism and is not visible. The edge of the front face 85*a* of the prism 83 is also shown in FIG. 5.

In practice, it may be desirable to form the prism 83 from one solid piece of transparent material in which case there will be no actual face 85*a* as indicated. However, the overall effect will be the same.

A second portion 83*b* of the prism 83 is also formed in the shape of a triangular prism; in this case a triangular face is visible in FIG. 5. Although the portion 83*b* of the prism 83 is shown as a right triangular prism in FIG. 5, there is no necessity for the right angle corner of the prism to be accurately formed, and in fact this angle need not be a right angle.

The front face 85*b* of the prism 83 is disposed at an angle to the longitudinal axis of the cavity 81 which is approximately equal to the cavity 81 which is approximately equal to the Brewster's angle for the prism 83. The Brewster's angle is that angle at which a wave polarized parallel to the plane of incidence is wholly transmitted (with no reflection) and a wave polarized at right angles to the plane of incidence is substantially totally reflected.

The prism 83 is preferably shaped so that rays incident upon the face 85*b* at the Brewster's angle (indicated by the angle θ_b in FIG. 5) are refracted to be approximately perpendicular to the face 85*a* of prism 83*a* (or in the

event that portions 83*a* and 83*b* are formed from a single unitary piece of transparent material, then the plane separating these portions).

A second prism 86 is located at the other end of the cavity 81. The prism 86 is a right triangular prism oriented so that one triangular face is visible in FIG. 5. The edges of three rectangular faces of the prism 86 are visible in FIG. 5, namely those of reflecting faces 87*a* and 87*b* and of front face 88.

Front face 88 is also disposed at an angle with the longitudinal axis of the cavity 81 equal to Brewster's angle for the material of which prism 85 is formed. This angle is indicated by θ_b.

Prism 86 is preferably cut so that rays incident upon face 88 at Brewster's angle are refracted to strike reflecting faces 87*a* and 87*b* at approximately an angle of 45°.

Due to the angle of incidence of the rays on the faces 85*b* and 88 of the prisms 83 and 86, respectively, in FIG. 5, the optical system of FIG. 5 functions not only to provide a closed path for light rays, but also to reject the light having other than a particular polarization. At the same time the problem of partial reflection of light from the front face of the prism is substantially eliminated by the orientation of these faces.

A window 89 is provided in the cavity 81 arranged to receive light reflected from the front face 88 of prism 86. From the previous explanation it will be understood that there would normally be no reflection of light generated in the cavity from the face 88, as there would be a closed path (and amplification) provided only for light of a particular polarization and this light would be totally transmitted through face 88. However, in order to provide an output from the cavity 81, the face 88 may be rendered partially reflecting by the addition of a coating, for example. An output may be provided also by setting the prism 86 at an angle differing somewhat from Brewster's angle and thereby causing a small amount of reflection of the polarized light generated within cavity 81. In some instances it may be desired to control the reflectivity from the face 88, which will, among other effects, control the output from the cavity 81; this may be accomplished by rotatably mounting the prism 86 so that the angle of incidence of rays with the front face 88 may be controlled by rotating the prism 86 about an axis perpendicular to the plane of the paper.

From the foregoing explanation it will be understood that FIG. 5 represents a preferred form of optical system which may be utilized in the light amplifying apparatus of FIG. 4 or others of the resonant light amplifiers, and which provides the advantage of substantially eliminating unwanted reflection from the front face of the prism, and at the same time provides a polarized output which is obtained by a filtering action inside the cavity 81. Such filtering action within the closed path inside the cavity is preferred to filtering the output from the light amplifier due to the fact that the approximately 50% power loss resulting from external polarization is substantially eliminated. The optical system of FIG. 5 also allows the reflectivity of the face 88 to be continuously controlled and thus allows controlling of the output from the light amplifier.

In addition to being useful in resonant light amplifiers, the optical system of FIG. 5 is useful in other applications where a light resonator is employed such as in a Fabry-Perot interferometer.

Mirror type resonant light amplifier

FIG. 6 shows an alternative form of resonant light amplifier device comprising a cavity 101 having transparent side walls and enclosed at its ends by flat mirrors 102 and 103.

The interior 104 of the cavity 101 is filled with a sensitized working medium such as sodium vapor. Placed around the cavity 101 is a concentric cylindrical discharge tube 105. The surface 106 may be provided with a reflective coating to conserve light while the inner wall 107 of the discharge tube 105 is transparent to the desired component of the light produced in the discharge tube.

Electrodes 108 are provided in the discharge tube 105 which are supplied with power from a power supply 109 through leads 111.

In the form of apparatus shown in FIG. 6 the medium in the gas discharge tube 105 is a mixture of sodium and mercury. As previously explained, such a mixture provides an enhancement of a desired spectral line by collisions of the second kind. This brings about a considerably increased intensity of the desired spectral line in the lamp and increases the optical pumping power which creates the desired population distribution in the energy levels of the atoms of sodium in the interior 104 in the cavity 101 conducive to stimulated emission of light radiation.

In FIG. 6 the reservoirs, ovens, and auxiliary equipment for maintaining the proper atmosphere in the discharge tube 105 and in the cavity 101 have been omitted for simplicity. Such elements may be provided for the apparatus of FIG. 6 in accordance with other figures of the drawings or any other suitable means for maintaining the appropriate atmosphere may be utilized.

The mirrors 102 and 103 may be metallized or multilayered interference reflectors. The latter are almost lossless (i.e., the transmission plus the reflection equals approximately 100%). Interference reflectors may have a very high reflectance, for a given wavelength, depending on the number of layers. A practical achievement is 98% in the visible for a 7-layer reflector. Flats with a closer tolerance than approximately $\frac{1}{50}\lambda$ are not currently available so if a resonant system is desired and more accurate flats are not available, higher reflectance would not be useful. An additional advantage of interference reflectors is that photons from other than the desired transition would not be reflected (due to frequency selectively), and hence, undesired stimulated transitions would be prevented.

It is clear from FIG. 6 that a plane wave travelling in a direction other than 90° to the mirror surface will "walk" off the edge and lose energy at a rate faster than the normal wave. The lateral displacement per reflection is

$$x = L \sin\theta \cong L\theta$$

The fraction of wave energy which walks off at each reflection is roughly

$$\frac{x}{2R} = \frac{L\theta}{2R}$$

So the effective loss coefficient on reflection is

$$\alpha = \alpha_{abs.} + \frac{L\theta}{2R}$$

where $\alpha_{abs.}$ is the loss at the reflector due to absorption and diffraction, or the rate of energy loss is

$$-\frac{1}{E}\frac{dE}{dt} = \alpha = \frac{ac}{L} = \left[\frac{a_{abs.}}{L} + \frac{\theta}{2R}\right]c$$

As α increases, the gain of the light amplifier will decline proportionately in the range of linear amplification. A practical measure of the limiting angle at which effective amplification obtains might be that angle for which

$\alpha = 2\alpha$ absorption:

$$\frac{\theta_2}{2R} = \frac{a_{abs.}}{L}$$

or

$$\theta_2 = \frac{2aR}{L}$$

the maximum one might conceive would be $\theta_2 \sim 0.1$ radian, while for the dimensions immediately above,

$$\theta_2 \sim 5 \times 10^{-4} \text{ radian}$$

The fact that the loss coefficient falls off with increasing

angle, θ, determines a most important characteristic of the resonant light oscillator output, a very narrow beam.

It can be calculated that virtually the entire output beam will fall within the Farunhofer diffraction pattern for $\theta=0$. It may also be shown that, with $P_{out}=1$ watt at $\lambda=1\mu$, the frequency bandwidth of the output beam will be less than 100 cycles/sec. This is residual oandwith due to the noise discussed below.

As pointed out previously, the random-fluctuation spontaneous emission background in the visible will correspond to transitions induced by thermal radiation at a temperature of 30,000° K. However, this is not so high as it first appears, since a resonant light amplifier may discriminate against all signals outside a narrow optical band and against all directions of propagation out of the central Fraunhofer lobe.

It can be estimated that the minimum equivalent noise input power in a Fraunhofer lobe is given by:

$$P_{min}\approx 1.5\times 10^{-11} \text{ watts in the visible}$$

If the bandwidth, Δ_f, is limited in a succeeding electronic amplifier, it can be shown that the following expression for this noise holds

$$P_N=h\nu\left[\frac{\pi}{2}\Delta\nu\Delta_f\right]^{1/2}$$

Thus the minimum noise depends on the square root of the bandwidth but not on the area of the reflectors **102**, **103** at the tube ends.

The apparatus of FIG. 6 may be used as an amplifier as distinguished from a self-sustained oscillator by limiting the "gain"; that is, by limiting the amount of light power introduced from the discharge tube **105** so that a self-sustained oscillation is not produced. A signal may, therefore, be introduced through the mirror **103** as indicated by the arrow **112** as the mirrors **103** and **102** are partially transmitting.

The light ray indicated at **112** will cause stimulated emission of light energy within the cavity **101** which is coherent with the input signal with respect to phase, frequency and direction of propagation. The amplification within the cavity is rather selective with respect to direction of propagation and frequency so that only a relatively small range exists with respect to these two parameters within which an input wave will be amplified in the device.

The output from the light amplifier will be transmitted through mirrors **103** and **102** as indicated by the arrows **113** and **115**. Either or both of these outputs may be utilized, depending upon the particular application or system in which the light amplifier is used.

As in the case of previously discussed light amplifier devices, the device of FIG. 6 may also be utilized as an oscillator simply by increasing the efficiency of the process or otherwise increasing the gain of the amplifier to the point where self-sustained oscillations are produced. In certain applications it may be desirable to utilize the same apparatus as both an oscillator and an amplifier, on a time sharing basis, for example. This may be accomplished, for example, by periodically increasing the light energy produced by the discharge tube **105** to momentarily produce self-sustained oscillations. It should be understood that the optical system can be replaced by other optical systems such as those illustrated in FIG. 4 and FIG. 5, and also that the exciting process utilized in FIG. 6 may be replaced by other exciting processes previously described.

It should be noted that the apparatus of FIG. 6 does not differ greatly from the nonresonant cylindrical amplifier previously described, and the resonant apparatus in FIG. 6 could be converted to a nonresonant amplifier by substitution of diffuse reflectors for the mirrors **102** and **103**.

Resonant light amplifier with internal discharge

The technique of exciting the atoms within the cavity may be applied to resonant light amplifiers as illustrated in FIG. 7. An elongated cavity **121** is provided having enclosed ends **122** and **123**. Desirably at least one of the ends such as **123** is transparent to light of the frequency for which the amplifier is designed. In the case of the cavity **121** the side walls need not be transparent as in previously described cavities because there is no necessity for introducing light energy through the walls, as different means of excitation are used.

The interior **124** of the cavity **121** is provided with a gaseous atmosphere which may be supplied from a reservoir **125** heated by a heating coil **126** controlled by a temperature regulator **127**. As previously described in the explanation of other forms of the apparatus, the elements **125**, **126** and **127** in conjunction with a temperature control oven **130** surrounding the cavity **121** assure that the pressure of the medium within the cavity is maintained at the proper value.

Preferably the interior **124** of the cavity **121** is filled with a gaseous atmosphere comprising a mixture of sodium and mercury, or with some other mixture of elements by means of which the efficiency of exciting the working atoms to a desired energy level is enhanced by reason of collisions of the second kind. The general theory by which more desirable population distribution among the energy levels of one element is produced by collisions of the second kind with another element has previously been explained and will not be repeated here. The optical system of the device of FIG. 7 is similar to those previously described in that it comprises two prisms **131** and **134** having 90° angled faces **132** and **135**, respectively, and front faces **133** and **136**. As previously explained, the front faces **133** and **136** are preferably provided with a low-reflection coating so that substantially all of the reflection is by internal reflection from the faces **132** and **135**.

At least one of the faces **135** may be provided with a coating of a medium having an index of refraction intermediate between that of the prism **134** and the atmosphere in which it resides thus preventing total reflection at the face **135** and allowing transmission of light generated within the cavity **121** through the prism **134**. It may be noted at this point that light passing through the prism **134** may be divided into several beams by reflection and refraction. In some cases this may be desirable, but in the event that it is desired to direct substantially all of the output beam in one direction, additional prisms can be provided for combining the various output beams by reflection or refraction to be directed substantially in the same direction.

An optical filter **137** may be included in the light path between the prisms **131** and **134** for the purpose of discriminating against light of a frequency other than that selected for the operation of the light amplifier. Particularly when such amplifier is operated as an oscillator, there may be an atomic transition of higher probability than that generating the desired light frequency. Such a transition would generate an oscillation at a lower input power than required for the desired oscillation. Such parasitic oscillations must be suppressed. Generally, oscillation in several modes simultaneously will not occur, except as transients, and would in any case be undesirable. Accordingly, it may be desired to place an optical filter such as **137** within the cavity **121**, thus reducing the gain for all except the desired frequency of light below the point required for sustained oscillation.

Another and different use for a filter (such as filter **137** within the cavity **121** as shown in FIG. 7) is for the purpose of providing a polarized light output from the light amplifier. Obviously the introduction of a polarizing

filter within the closed path in the light amplifying device will introduce losses for light of all that the polarity for which the filter is transparent. These losses will greatly degenerate the amplification for other than the desired polarity of light and in an oscillator type device will prevent the generation of self-sustained oscillations except for light of the desired polarity.

The operation of a resonant light amplifier with a polarizing filter is therefore similar to that described for the apparatus of FIG. 5 which also includes polarizing means within the closed light path in the light amplifier. As in the case of the apparatus of FIG. 5, polarization within the light amplifier device has advantages over polarizing the light output from the device, in that loss of substantially half of the power, as would occur in polarization of the output, is substantially avoided. Furthermore, in some instances the light intensity may be sufficiently high in the output so that polarization of the light would present a heat dissipation problem. When the light is polarized within the light amplifier device, it is polarized before light of the unwanted polarization has a chance to build up in intensity and accordingly the heat or energy dissipation problem is substantially reduced.

It will be noted that in the apparatus of FIG. 7, no separate gas discharge lamp is provided for light excitation of the medium within a cavity. Instead a discharge is excited directly within the cavity **121** by means of electrodes **120** connected to a power supply **128** through leads **129**.

Electrodes **120** in FIG. 7 are arranged inside the cavity **121** and may be energized to provide either a direct current or low frequency discharge. It is not necessary however, that the electrodes be within the cavity to produce a discharge within the cavity. For example, electrodes outside the cavity formed of aluminum foil or the like may be utilized to induce an R.F. electric discharge in the cavity **121**.

As previously explained, producing the discharge within the cavity provides the immediate advantage of increased energy transfer into the medium within the cavity. Virtually complete transfer of energy into the medium can be accomplished by this means whereas excitation by a light source is limited to approximately 20% absorption of the light power introduced into the cavity. Other advantages of excitation by discharge within the cavity also arise.

The higher S-levels of sodium cannot be excited by resonance radiation since radiative transitions between states of the same orbital angular momentum are forbidden by the electric dipole selection rule. However, they can be excited by collisions of the second kind in a discharge within the cavity. In the case of excitation of Na ($7^2S_{1/2}$) by collisions with Hg (6^3P_0) metastables, the Wigner partial selection rule relating to collisions of the second kind is satisfied and the collision cross-country may be expected to be about equal to that for excitation to the $6^2P_{1/2}$ Na level. The enhancement of population should be at least 100 times that in a sodium-argon discharge. One may expect to exceed the condition for oscillation in this case by a factor of 20 (for a tube 1 cm. diameter and 100 cm. length).

It can be seen from the diagram in FIG. 2 that, in addition to light amplifier oscillation via the 12,920 A. ($7S \rightarrow 4P$) transition, there is the possibility of light amplifier oscillation in the visible 4751 A. ($7S \rightarrow 3P$) transition in sodium. Although the Einstein "B" coefficient is larger for the former than for the latter transition, the ($7S \rightarrow 3P$) or any other particular transition can be favored by inserting filters to absorb all other wavelengths or by using multiple layer reflectors (which reflect only a narrow band of wavelengths). Thus only for the selected transition will losses be small enough to permit the buildup of oscillation.

The pressure of sodium, and hence the operating temperature of the light amplifier tube, may be smaller since the density of Na atoms need only be large enough to ensure an adequate number of collisions/sec. with metastable Hg atoms ($p_{Na} \approx 10^{-4}$ mm. Hg) rather than enough to absorb the ($6P \leftarrow 3S$) resonance radiation.

This lower pressure can be arrived at as follows. It is known that under the usual conditions in a plasma the populations of metastable states are in thermal equilibrium at the electron temperature (of the order of 5000° C. for a Na-Hg discharge). Hence, the population of Hg (6^3P_0) metastables will be $\sim 10^{-4}$ of Hg (6^1S_0), the ground level, in a discharge of a few amperes. In a total pressure of 10 mm. Hg of Hg, the metastable partial pressure would be 10^{-3} of Hg or a density, $N \approx 10^{13}$/cm.^{3}.

The rate at which a sodium atom is excited to the 7S or 6P levels must correspond roughly with rates of quenching by collisions of the second kind in the case of N_2 and other such gases. For a partial pressure of Hg (6^3P_0), $P \approx 10^{-3}$ mm. Hg, this rate of Na excitation would be $\gamma Na \geqq 10^5$ sec. For a sodium pressure, $P \approx 10^{-4}$ mm. Hg or $N_{Na} \approx 10^{12}$/cm.^{3}, the total excitation ratio $\approx 10^{17}$/cm.^{3} sec. For a light amplifier tube of volume 100 cm.^{3}, this gives 10^{19} excitations/sec., or about 30 times the calculated necessary rate. If this power is substantially used to generate coherent photons by light amplifier action, a beam power of

$$P = h\nu \frac{dn}{dt} \cong 2 \text{ watts}$$

will be produced.

Conversely the rate at which Hg metastables are attacked by Na atoms will be $\sim 10^4$ sec for a metastable life-time $\tau \approx 10^{-4}$ sec. This is at least 100 times shorter than the diffusion time to the walls and hence there will be practically no useless loss of metastables via this mechanism. Thus the efficiency of conversion will be relatively high (of the order of 10 percent of input power). The discharge current must, of course, be sufficient to keep up the equilibrium population of metastables. A discharge power, $P = 3$ amps $\times 0.3$ volt/cm. $\times 100$ cm. $= 100$ watts should normally be adequate.

Other atomic levels excitable in a discharge

In addition to the excitation of the Na (6P and 7S) levels by collisions of the second kind with Hg (6^3P_0) metastables in a discharge within the light amplifier tube, a number of other energy levels are prospectively suitable for excitation in a discharge. These other levels could not normally be expected to be excited by radiation falling on the tube from outside, either because radiation-induced transitions from the ground level are forbidden,, or because the exciting radiation falls too far in the ultraviolet to pass through even the most transmissive medium such as a quartz tube wall.

A list of metastable levels which may be used to excite levels of nearly the same energy in other atoms by collisions of the second kind is given in Table I. These levels are long-lived because the electric dipole selection rules prohibit decay via this rapid radiative process to any lower level. Metastable levels are listed only for atoms which normally form a monotomic gas (uncombined in molecules) though others could possibly be utilized. Table I is not complete but contains levels most likely to be of practical use. The alkaline earth elements and Zn, Cd are not easily vaporized.

The processes listed below are not analyzed in great detail, but are listed as likely to be useful in particular cases or applications where particular frequencies or other characteristics are desired.

TABLE I

Element	Metastable Levels	Energy Above Ground	Ionization Potential
Sn (v.)		2	7.3
Pb		4	7.4
Be, Mg, Ca, Sr, (Ba)	n^3P_2, n^3P_0		
Zn	4^3P_2, 4^3P_0		9.39
Cd	5^3P_2, 5^3P_0	3.73	9.00
Hg	6^3P_2	5.4	10.434
	6^3P_0	4.642	
He	2^3S_1	20.55	24.581
	2^1S_1	19.77	
Ne	"$^3P_2$"	16.53	21.559
A	"$^3P_2$"	11.49	15.75
Kr	"$^3P_2$"	9.8	13.996
Xe	"$^3P_2$"	8.30	12.127
Rn	"$^3P_2$"		10.746
Tl	$6^2P_{3/2}$	0.97	6.1

Light amplifier action in a helium discharge

The lowest non-metastable level of He is so high (2^1P_1 at 21.1 volts) compared to the spacing of the next higher level (3^1S_0 at 22.9 volts) and compared to the ionization potential (24.58 volts), that two unusual consequences are true.

Firstly, the decay rate

$$A(2^1P_1 \rightarrow 1^1S_0) \approx 10^{10}/\text{sec}$$

while

$$A(3^1S_0 \rightarrow 2^1P_1) \approx 10^7/\text{sec}$$

or 1,000 times slower.

Secondly, the electron temperature in a helium discharge is very high, of the order of 25,000° C. or ~2.5 electron volts average electrons energy at about 1 mm. Hg discharge pressure, up to 200,000° C. at very low pressures (10^{-2} mm. Hg). The Maxwell distribution of kinetic energies in a perfect gas at thermal equilibrium is

$$\frac{dn}{n} = 2\sqrt{\frac{E}{\pi}} \frac{e^{-E/KT} dE}{[KT]^{3/2}}$$

So the ratio of numbers of electrons having energies E_h and E_l is

$$\frac{dn_h}{dn_l} = \sqrt{\frac{E_h}{E_l}} e^{\frac{-(E_h - E_l)}{KT}}$$

The ratio of excitation rates to the 3^1S_0 and 2^1P_1 levels by electron collisions will be roughly equal to dn_2/dn_1. Since $E(3^1S_0) - E(2^1P_1) = 1.7$ electron-volts and $KT \approx 2.5$ e.v., it will be seen that the rate of excitation by electrons is almost the same for both levels, while the rate of decay from 2^1P_1 to the ground level is almost 1,000 times greater. One may, therefore, expect an excess population in 3^1S_0 over that in 2^1P_1.

This does not take account of factors which will tend to raise the population of 2^1P_1:

Firstly, most of the atoms excited to higher levels must decay via the 2^1P_1 level.

Secondly, the photons emitted during the processes

$$2^1P_1 \rightarrow 2^1S_0$$
$$2^1P_2 \rightarrow 1^1S_0 \text{ (ground)}$$

will be trapped in the gas and re-excite atoms to 2^1P_1. However, it appears that in at least some instances a pure He discharge will be desirable for use in a light amplifier device according to the present invention. A similar trapped photon situation exists for the Na($7S \rightarrow 3P$) transition.

Other cases of excitation by collisions of the second kind

In addition to the selective excitation of Na(7S or 6P) by collision with metastable Hg(6^3P_0) atoms in a discharge, there are listed in Table II other atomic metals which may be excited by collision with metastables. In each case higher levels of the working element fall near metastable levels of a possible carrier gas. In some cases such "sensitized fluorescence" has already been observed by experimentors. For a fuller understanding of Table II, refer to Table I.

It is obvious that light amplifiers in different frequency ranges will be desired for various different applications and thus this characteristic of the type of discharge utilized, as well as others of its characteristics in addition to its inherent efficiency, will be considered in selecting the medium utilized in a light amplifier.

TABLE II.—SOME COLLISIONS OF THE SECOND KIND

Carrier Gas	Carrier Metastable Level	Initial Level of Working Atom	Excited Level of Working Atom
Hg	6^3P_0 (4.642 v.)	Tl ($6^2P_{3/2, 1/2}$)	Several
Hg	6^3P_0 (4.642 v.)	In ($5^2P_{3/2, 1/2}$)	Do.
Hg	6^3P_0 (4.642 v.)	Hg $6^3P_0 \rightarrow 8^1S_0$	(9.20 v) ($\Delta E = 0.08$ v.)
		$\downarrow$	
		6^1P_1 + 4,916 A.	Photon
		$\downarrow$	
		6^1S_0 + 1,899 A.	Do.
He	2^1S_0 (20.55 v.)	Ne (2^1S_0)	
	2^3S_1 (19.77 v.)		
A	4^3P_2 (11.49)	Kr (4^1S_0)	
Kr	5^3P_2 (9.84)	Hg (6^1S_0)	$8^1D, 8^3D$
		Xe (5^1S_0)	
Xe	6^3P_2	Hg	

Light amplifier transitions from metastable to ground level

In all the transitions discussed so far, the spontaneous decay rate of the excited level was $>10^6$/sec., characteristic of "allowed" electric dipole radiative transitions. Since the excitation rate is of the order of 10^5/sec. even using the efficient and selective method of collisions of the second kind, it is evident that the excited level population could not be made greater than the ground level. Thus light amplifier action or emission by mutually-induced transitions could occur only to an intermediate level whose population was kept lower by an even faster rate of spontaneous decay.

It is also possible to depopulate a longer lived lower level by collisions of the second kind, to accomplish the same result.

This situation is in contrast to that of the Maser. For levels spaced only by $E = h\nu$ where ν is a microwave frequency, the thermal equilibrium population of the excited level is high and the lifetime is long. Therefore, the population of the excited level is easily maintained above that of the ground level.

In the case of levels high above ground (optical transitions), the initial populations will always be low. But if the levels are long-lived (metastable), it may be possible to populate them at a rate greater than the natural decay rate or relaxation rate, and hence to maintain a higher population of atoms in the higher state.

Many of the elements which exist as single atoms in the gaseous state do not have high vapor pressures at convenient temperatures. Therefore, those which may possess metastable states are not useful in exciting other atoms by collisions of the second kind. Nevertheless, it may be possible to use such atoms as working atoms as described above. For this purpose the pressure may be much lower. Most of these metastable levels are listed in Table I.

As an example, consider the case of zinc. The metastable 4^3P levels lie about 4 electron-volts above ground

as shown in FIG. 14. These levels do not lie close to any other metastable levels and so cannot be excited directly by collisions of the second kind. However, higher, non-metastable levels of Zn, can be excited by collisions with metastable krypton and xeron. From these levels the Zn atoms decay rapidly to the metastable levels as well as the ground level.

The rate of decay of Zn ($4^3P_1 \rightarrow 4^1S_0$) by emission of the ultraviolet photon, $\lambda = 3076$ A., is $A = 1 \times 10^5$/sec It has already been mentioned that rates of collision excitation somewhat greater than this may be achievable. Therefore, it should be possible to generate light amplifier transitions directly to the ground level with zinc. One must have

$$(N_{high} - N_{low}) = N_{high} = \frac{\bar{a} 8\pi}{c\lambda^2 f(\nu_0) A}$$

Substitution of values gives $N_{Zn(3P_1)} > 5 \times 10^{11}$/cm.^{3}. If the atoms are shared by collision among the three metastable levels, the required zinc pressure is only 2×10^{-5} mm. Hg, which is the vapor pressure at about 200° C.

In the case of thallium, most of the atoms may be pumped into the much longer lived $6^2P_{3/2}$ metastable level by a similar indirect mechanism: either collisions of the second kind with Hg metastables or absorption of the 3776 A. resonance radiation with subsequent decay to $6^2P_{3/2}$.

In this case, since

$$A(6^2P_{3/2} \rightarrow 6^2P_{1/2}) \approx 50/\text{sec.},$$

the density must be quite high: $N \approx 10^{14}$ atoms/cm.^{3} or $P \approx 3 \times 10^{-3}$ mm. Hg at a temperature, T 600° C.

Excitation by coincident spectral lines

Previously, the excitation of atoms by resonance radiation was discussed. The emitted spectral lines from a lamp of the same substance necessarily coincide with frequencies absorbed most strongly by the same type atoms in the light amplifier. However, as pointed out in the discussion of sodium excitation, the intensities of lines emitted from the lamp during decay of higher states are quite weak. It was also pointed out that the intensity of certain of these higher resonance lines could be enhanced by collisions of the second kind with metastable atoms. Another way of obtaining strong excitation to higher electronic levels is by accidentally coincident bright emission lines from another atom.

The chance coincidence of two appropriate atomic lines is small. There is room for some 300,000 spectral lines of Doppler width with only slight overlap throughout the visible and near ultraviolet range. There are at most 1,000 useful resonance transitions in convenient atoms and approximately 30 bright atomic lines with which to excite them. Thus, there is about a 10% chance of one good coincidence. At least three moderately close coincidences are known, as shown in Table III.

He ($3^3P \rightarrow 2^3S$)	3889 A.	$\approx$ Cs($8^2P_{3/2} \leftrightarrow 6^2S_{1/2}$) 3889 A.
Zn	3303.7 A.	$\approx$ Na($4^2P_{1/2} \leftrightarrow 3^2S_{1/2}$) 3303 A.
A	8521.4 A.	$\approx$ Cs($6^2P_{3/2} \leftrightarrow 6^2S_{1/2}$) 8521.2 A.

However, in none of these cases is the overlap good enough for high excitation efficiency. On the other hand numerous examples of the excitation of molecules by coincident atomic lines have been observed.

Information is scarce on fluorescence of molecules containing more than two atoms. Therefore, only diatomic molecules are considered herein.

Each electronic level in a diatomic molecule is split into approximately 50 vibrational levels and each vibration level into approximately 200 rotational levels.

Therefore, we may expect more than 100,000 absorption transitions from populated levels in every molecule on the average. As expected, there is generally at least one coincidence of a bright atomic spectral line with some resonance transition of a given molecule. By the same token the emission from a discharge in a molecular gas is divided into many weak lines. These cannot be excited by an external lamp conveniently.

Materials which transmit U.V. radiation below 2,000 A. are not available. Therefore, the light amplifier process previously described cannot be used, i.e. excitation to a high electronic level with light amplifier emission to an intermediate level whose population is kept low by rapid spontaneous decay to a ground level. Instead the properties of molecules require and permit another mechanism for keeping the lower level population lower than some higher level population. This mechanism is relaxation of the lower level population by collisions of the second kind.

To exemplify the whole process, the molecule I_2 is considered (see FIG. 8).

The first member of the sodium principle series at 5893 A. (see FIG. 2) coincides with one of the numerous absorption lines of the iodine molecule. The transition in question is from a rotational sublevel of the $v=2$ vibrational level of the ground electronic state ($\epsilon' g^+$) up to the $J=30$, $v=17$ sublevel of the ($3\pi_0^+$) state. The $v=2$ of ($\epsilon' g^+$) levels are well populated in thermal equilibrium at room temperature (see lower right corner of FIG. 8), while $v=7$ of ($\epsilon' g^+$) has less than 1% of the population and $v=17$ of ($3\pi_0^+$) has none.

A 1 cm. thick layer of I_2 vapor at a few mm. Hg pressure absorbs most of the Na light and raises I_2 molecules to the upper level at a rate

$$\frac{dn}{dt} = \frac{P_{avail}}{h\nu}$$

In the absence of light amplifier action, the atoms decay at a rate

$$\frac{dn}{dt} = n_h[\gamma_c + \epsilon \text{ (all other states)}]$$

where:

ϵ_A=spontaneous radiative decay rate,

n_h=population of atoms in the higher energy state, and

γ_c=rate of removal by relaxation collisons with other I_2 molecules (quenching collisions). The cross-section for these collisions is very high since many I_2 states are closely spaced in energy. About 5% of the molecules decay to $v=7$ of ($\epsilon' g^+$). Then, by the same method of decay as that first described herein, the dynamic equilibrium rates of population change are

$$\frac{dn_h}{dt} = 0 = \frac{P_{avail}}{h} - n_h(\gamma_c + \epsilon A)$$

$$\frac{dn_l}{dt} = 0 = n_h A(h \rightarrow l) - n_l \gamma_c$$

and

$$n_h = \frac{P_{avail}}{h\nu(\gamma_c + \epsilon A)}$$

$$\frac{n_h}{n_l} = \frac{\gamma_c}{A(h \rightarrow l)}$$

It is to be noted that atoms can be removed from $v=7$ of ($\epsilon' g^+$) only by relaxation collisions to other sublevels of the ground electronic state. Then if the I_2 pressure (~ 5 mm. Hg) is such that

$$\gamma_c \sim \epsilon A_h \sim 20 \times A(h \rightarrow l) \sim 10^7/\text{sec.}$$

then

$$n_h/n_l \approx 20 > 1$$

which is necessary for light amplifier action.

The further analysis is quite similar to that for the Na($6P \rightarrow 4S$) light amplifier transition. The values involved are not much different and so for a light amplifier tube 1 cm. diameter x 100 cm. long, the required Na (5893 A.) intensity from a discharge lamp arranged as a jacket is

1.5×10^{-3} watts/cm.^{2} steradian

As pointed out previously, the intensity in the first line of the Na principle series can easily be made greater than 0.1 watt/cm.^{2} steradian, with a factor of 100 to spare.

From the above explanation it will be seen that although a light amplifier may be constructed utilizing light energy from one substance to excite a different substance having a coincident spectral line, the known combinations of monatomic substances bordering on coincidence are not promising.

On the other hand, the coincidences of an atomic line with a resonance transition of a molecule often provides a very high degree of coincidence suitable for use as an excitation process in a light amplifier according to the present invention.

An example of such a coincidence usable as an exciting process is the coincidence of the first member of the sodium principal series at $\lambda=5893$ Angstroms which very nearly coincides with one of the absorption lines of the iodine molecule.

Construction of a light amplifier device utilizing this type of excitation would be generally similar to that previously described except that the excitation lamp would be a sodium discharge lamp while the working medium within the cavity would be iodine vapor.

Liquid or solid working substances

The "line" width $\Delta\nu$, of radiative transitions in ions, atoms or molecules within liquids or solids is generally quite broad because of continuous strong interaction with neighboring atoms. The uninterrupted phase lifetime,

$$T_2=\frac{1}{\pi\Delta\nu}\sim 2\times 10^{-13} \text{ sec. typically}$$

while the spontaneous radiative decay time remains long: $T_1>10^{-8}$ sec.

The effect of this is to raise the density of excited atoms, etc. required for light amplifier oscillation. This in turn raises the required illumination intensity for an externally excited resonant light amplifier:

$$I_{\text{available}}=\frac{\overline{\alpha}R4h\nu\sum A}{l\lambda^3 f(\nu_0)A}$$

The line shape factor,

$$f(\nu_0)=\frac{2}{\pi\Delta\nu}$$

for a Lorentz line, and approximately the same for other line shapes. Thus most condensed systems will require a high power input to excite light amplifier action.

An additional difficulty is that excitations in solids or liquids are usually "quenched" by non-radiative processes.

One should accordingly use substances which fluoresce (reradiate) with high quantum efficiency. Some substances which absorb the powerful Na (5893 A.) line and fluoresce efficiently are the merocyamine dyes, fluorescein, Meldola blue, and Rhodamine "B." More promising are certain substances in which the electrons which take part in the excitation lie in the interior of the atoms or ions concerned and are shielded from environmental perturbations. Such substances, including the porphyrins, ruby, and rare earth ions have much narrower lines.

The use of a polycrystalline solid entails the refraction and reflection of a light wave at the crystal interfaces, preventing the lossless reflection of a wave back and forth between light amplifier reflectors. To avoid this a single crystal ruby could be used.

The difficulties inherent in the use of solid or liquid working mediums may be minimized by use of, for example, the rare earth ion, Eu^{+++}, in liquid solution. The angular momentum sublevels of the first two electronic states are shown in FIG. 9.

The J-sublevels are further split into states and one of the components of the $J'=0\rightarrow J''=1$ transition overlaps the Na 5893 A. line. The upper J-levels are rapidly quenched to the lowest two J-levels ($\gamma\approx 1.5\times 10^{12}$/sec.) but transitions between the upper and lower electronic states occur only by radiative emission at the slow "forbidden" rate, $\gamma\approx 10^3$/sec., in the case of europium sulfate in water.

The ions may be excited by sodium radiation to $J'=2$ and decay to any of the J'' levels. The two strongest fluorescent transitions at $\lambda=8110$ A. and 6881 A. are suitable for a liquid filled light amplifier.

The J-quenching interaction gives rise to a line width $\Delta\nu\approx 5\times 10^{11}$ cycles per sec. or $\Delta\lambda\approx 6$ A. This line width is much sharper than those of other condensed fluorescent substances but broad compared to the spectral lines emitted by atoms in a low pressure discharge ($\Delta\lambda\approx 0.01$ A.). Therefore, one may artificially increase the power of the Na discharge lamp to get the necessary power without worrying about line distortion.

The necessary intensity of illumination is given by the equation for I available above and is between 0.1 and 1.0 watt/cm.-stere. A commercial "General Electric" lamp with broadened and reversed sodium lines emits just about this intensity.

Thus it appears that when for particular applications a condensed working substance, such as a liquid is desirable, such a working substance may be utilized in a cavity such as shown in FIG. 4, one example of such a working substance being europium sulphate in water. Excitation would be provided by a sodium discharge lamp similar to commercially available types with a broadened sodium line and emitting an intensity of between 0.1 and 1.0 watt per cm.^{2}-stere.

It will be appreciated that the various types of excitation discussed, such as excitation by resonance radiation, excitation by discharge within the cavity, etc., are generally applicable to both the nonresonant and resonant type of light amplifier apparatus, as are the various possible working mediums discussed.

Communication system

FIG. 10 shows apparatus providing a communication system and utilizing a resonant light oscillator according to the present invention.

Transmitter apparatus is indicated enclosed in dashed lines at **201**. Receiver apparatus is shown enclosed in dashed lines in the block designated **202**. Obviously, the transmitter and receiver would be separated by some distance depending upon the particular application for which the communication system is to be used.

In the transmitter apparatus **201**, there is incorporated a resonant light oscillator **203**, which may be any one of the various forms previously described. The oscillator **203** is provided with a power source **204**, and produces a light output in the form of a highly collimated beam of light having a quite narrow frequency bandwidth.

As previously explained, the wavelength (and, accordingly, the frequency) of the light produced will depend upon the medium utilized within the light oscillator. The particular application for which the apparatus is to be used will influence the selection of the medium within the oscillator in order to obtain light of a wavelength approximating that which is desirable in the particular case. For example, it may be desired to select the wavelength to minimized atmospheric absorption, particularly that due to fog, clouds, etc. in other instance, atmospheric absorption may not present a great problem and it may be desired to select the most efficient medium for production of light energy regardless of wavelength of the light output.

The output from the light oscillator **203** is passed through a Kerr cell modulator **205**. The characteristics of a Kerr cell are well known and will not be explained in detail. It will suffice to say that the Kerr cell provides an apparatus capable of being used as an electronically operated shutter for controllably presenting an opaque or a transparent cross-sectional area in the path of a light beam, thus allowing it to be turned off and on.

The Kerr cell has capabilities of operating at a rate on the order of 1,000 megacycles per second. Thus, it will be seen that the combination of the light oscillator and the Kerr cell may be utilized to produce a light beam modulated at a high frequency in response to an electrical input to the Kerr cell modulator.

The use of a Kerr cell involves the polarization of the light transmitted, and in FIG. 10 there is illustrated a polarizing filter 20 placed within the oscillator 203. This filter assures that the light ouput of the amplifier will be polarized thus obviating the necessity of polarizing the light output by external means.

Various advantages accrue by reason of the placement of the filter 200 within the enclosure of the oscillator 203. The filter 200 causes losses for light of unwanted polarization to be sufficiently great so that self-sustained oscillations for light of the unwanted polarization will not occur. As the emission is coherent with the respect to polarization, practically no generation of light of unwanted polarization will occur.

The available power is therefore substantially all utilized in producing the desired polarization and the energy normally required (amounting to approximately one-half the total) for producing the unwanted polarization is conserved.

In addition, any problem of heat dissipation in the filter is avoided as the filtering takes place prior to build-up of high energy density. Obviously the conventional technique of filtering the light output from the oscillator could be used if for any reason this was desired.

An amplifier and multiplexer 206 may be provided to supply a modulating signal to the Kerr cell 205. The information signal to be transmitted over the communication system is supplied to the amplifier multiplexer circuit 206. Normally, the information signal will be transmitted over numerous channels and combined in the multiplexer circuit.

The multiplexer is used to utilize the information transmitting capabilities of the system but is not essential for the operation of the system and the particular form of multiplexing apparatus utilized does not form a part of the present invention. The desirability of utilizing some multiplexing system to combine a number of signals of relatively narrow bandwidth into a single signal having a very wide bandwidth may be appreciated by a comparison of the possible bandwidths with a typical high information carrying signal. A light communication system with a bandwidth on the order of 1,000 megacycles would have the capability of carrying approximately 100 or more television channels of 6 megacycles each.

A particular advantage arises from the composition of the resonant light oscillator with the Kerr cell modulator from the fact that the light output from the resonant light oscillator basically has a very narrow spectral line of very high frequency. The Kerr cell must by its nature be designed for optimum operation at a particular wavelength and becomes inefficient or inoperative for wavelengths differing substantially from the optimum. Since the output of the oscillator 203 lies within a relatively narrow spectral line even when 1,000 megacycle modulation sidebands are added, it falls well within the fractional range of wavelengths for which the Kerr cell modulator operates efficiently.

The Kerr cell modulator also operates most efficiently for a highly collimated beam of light and the output of the resonant light oscillator also has this characteristic in a very high degree.

From the foregoing explanation, it will be seen that the transmitter 201 produces a modulated beam of light capable of carrying a large quantity of information in a bandwidth on the order of 1,000 megacycles or larger. From previously explained characteristics of the resonant light oscillator, it will be understood that the light energy is concentrated within an extremely small solid angle such that it will diverge by an amount which may be limited to 1 centimeter per kilometer or less (neglecting atmospheric effects which would have to be appropriately evaluated).

The receiver 202 may be provided with light gathering lenses 207 and 208, to increase the target area from which light intercepted from the transmitter will be supplied to the receiver. Obviously, other light gathering arrangements such as reflectors might also be used. In some cases, as in the case of short range transmission, light gathering apparatus may be unnecessary.

A resonant light amplifier 209 is arranged to amplify the light from the light-gathering lenses 207 and 208. *The resonant light amplifier may be of any of the forms* previously described but obviously will be selected to be compatible with the oscillator in the transmitter 201. The amplifier 209 is provided with a suitable power source 210.

The light output from the amplifier 209 may be taken from the end opposite the lenses 207 and 208 and directed by mirrors 211 if desired to a photocell demodulator 212. If preferred, the photocell demodulator 212 could be placed immediately adjacent to or incorporated as a part of the amplifier 209, or receive the beam directly without preamplification.

The photocell demodulator 212 may comprise any appropriate photoelectric, photoconductive or other photosensitive conversion apparatus for converting the light output of an amplifier 209 to an electrical output. The frequency response of the demodulator 212 should obviously be high enough to accommodate the bandwidth transmitted by the transmitter 201. The photocell apparatus 212 automatically acts as a demodulator in the sense that it is obviously incapable of producing an output of light frequency and accordingly produces a signal having the relatively much smaller modulation frequency.

The signal from the demodulator 212 must be supplied to an amplifier demultiplexer circuit 213 if a multiplexer is used at the transmitter. The amplifier demultiplexer 213 is the companion to the amplifier multiplexer 206 in that it is adapted to separate from a single channel the various signals of lower bandwidth which were combined in the multiplexer 205.

From the foregoing explanation, it will be seen that a communication system is provided which has a high efficiency and a very high information-carrying ability. The range of the system may be quite long, particularly in applications where atmospheric absorption would not be excessive. Even where atmospheric effects are troublesome, the wavelength of the light utilized can be selected in such a way as to substantially reduce difficulties from this source.

The system has a further advantage over wireless communication systems commonly in use in that the transmission path is limited virtually to a narrow cone which may not exceed more than a few feet at a widest point thus effectively preventing unauthorized interception of the information transmitted by the system. This characteristic in the system would normally make unnecessary scrambling apparatus and the like utilized to discourage interception of information in commercial communication systems.

It will be understood that the receiver may comprise any suitable photosensitive converter and need not include the resonant light amplifier 209. Similarly, the oscillator 203 need not be modulated by a Kerr cell but may be modulated in other fashions.

For example, modulation may be accomplished simply by modulating the "pumping" power source, if desired, although the modulation frequency so produced would be quite limited compared to the Kerr cell frequency bandwidth.

Frequency modulation of the resonant light oscillator output may be achieved by changing pathlength between reflectors; the frequency being highly dependent on this pathlength. For example, a reflector could be secured to or formed as a part of a piezoelectric crystal so that me-

chanical oscillation of the crystal would cyclically vary the pathlength between reflectors and accordingly frequency modulate the output.

Alternatively, the transition frequency of the working atoms, ions or molecules may be varied by means of magnetic or electric fields in the cavity (Zeeman or Stark effects). Such fields may be produced by a coil around the cavity, condenser plates on opposite sides of the column of working medium, or by placing the optical cavity in an electrical cavity or wave guide carrying the modulation signal. A change in the transition frequency will change the oscillation frequency.

In addition to making possible a frequency modulation instead of amplitude modulation of the light beam, these alternative modulation schemes may have other advantages such as power conservation and more convenient circuitry.

A frequency modulated light signal may be converted to amplitude modulation by passage through an optical filter having an acceptance frequency centered at or near the edge of the frequency swing of the frequency modulated light signal. For example, a resonant light preamplifier at the receiver would serve as a filter having the required frequency sensitivity.

Frequency or time measuring device

FIG. 12 shows apparatus for measuring frequency or time utilizing the constant frequency characteristic of the light output from the nonresonant-type light oscillator.

Two nonresonant light oscillators 301 and 302 are energized respectively by coils 303 and 304 which create discharges within the oscillators. The coils 303 and 304 are connected by leads 305 and 306 to a suitable source of radio frequency power. The light oscillators 301 and 302 are provided with gas fills as indicated at 307 and 308, which are excited by reason of the discharge generated therein. Egress for light energy from the light oscillators is provided by respective windows 311 and 312 through which the output of the oscillators is transmitted.

It will be understood that the oscillators 301 and 302 need not be of the radio frequency excited type but may be any type of light oscillator disclosed hereinbefore or any variation thereof. The oscillators 301 and 302 are, however, preferably of the nonresonant type as they are not particularly affected in frequency by changes in the dimensions of the cavity. The resonant light oscillators have an output frequency which is highly dependent on the distance between reflectors (i.e., the "cavity" dimension). This frequency dependence on dimension would normally render the resonant oscillator unsuitable for this frequency standard application, although in special circumstances this may not be so.

Lenses 313 and 314 are used to direct the light outputs from the oscillators 301 and 302 to a common point on the input of a photoelectric detector 315. The frequencies of the light output from the oscillators 301 and 302 (or their harmonics) differ by an amount within the frequency response of the detector 315.

Different frequencies may be obtained from the oscillators 301 and 302 by utilizing different gas fills 307 and 308. In some cases, the gas fills 307 and 308 may be the same and a different transition may be selected by means of filtering, or any other suitable technique may be utilized for providing suitably differing frequency outputs from oscillators 301 and 302.

The outputs from the oscillators 301 and 302 falling on the input of the detector 315 will cyclically interfere and reinforce at a rate equal to their frequency difference or the frequency difference of their harmonics. In other words, the two beams will heterodyne to produce a difference frequency which must of course be within the frequency response of detector 315.

It will be appreciated that any departure in frequency by either of the oscillators 301 or 302 will represent a percentage departure in the heterodyne frequency detected by detector 315 which departure will vary percentagewise inversely as the heterodyne frequency; accordingly, the heterodyne frequency should generally be selected to be as high as possible. It may, therefore, be desirable to use a detector 315 which utilizes microwave techniques thereby allowing a maximum heterodyne frequency on the order of a thousand megacycles.

Any suitable indicator 316 or other utilization device may be provided in accordance with accepted frequency standard techniques. For example, the frequency output of the detector or a submultiple thereof may be counted cycle by cycle to provide a direct and highly accurate comparison of frequencies.

The long-term accuracy of the frequency standard apparatus of FIG. 12 is theoretically predictable to be as high as 1 part in 10^{11} or better under certain conditions. This is considerably better than presently available microwave frequency standards and may be appreciated by the fact that it represents a variation less than one second from the year 1000 B.C. to the present (one second in 3000 years). The apparatus of FIG. 13 also provides a practical frequency standard in the region of light frequencies where none exists at present.

Interferometric apparatus

FIG. 13 shows apparatus for measuring distances using the techniques of interferometry and incorporating a nonresonant light oscillator according to the present invention.

A nonresonant light oscillator 321 is provided with an excitation coil 322 connected by means of electrical leads 323 to a suitable source of radio frequency energy thereby producing a discharge within the oscillator 321. The oscillator 321 is provided with asuitable working medium 324 and has a window 325 from which the light output of the oscillator is available. The oscillator 321 may be of the type described in connection with FIG. 12, or as in the case of FIG. 12, any type of light oscillator previously described or suggested hereinabove may be utilized for the light oscillator 321.

Suitable means is provided for directing the light from the oscillator 321 into a beam, such as a collimating lens 326. Light rays are indicated at 327 emerging from the lens 326 after having been collimated thereby.

The rays 327 strike a semi-transparent mirror 332 and are thereby reflected in part in an upward direction as indicated by the arrows 328 and are in part transmitted through the mirror 332 as indicated by the arrows 329. The rays indicated by the arrows 328 are substantially totally reflected from a mirror 333 and once again strike the semitransparent mirror 332 and are partially transmitted to form a part of the beam indicated by the arrows 331. The portion of the light rays indicated by arrows 328 which is reflected from the mirror 332 does not enter into the operation of the apparatus.

The rays indicated by the arrows 329 are reflected by a mirror 334 which is movable by a suitable translating mechanism such as the screw thread mechanism indicated at 335 and the rotatable handle at 336. The mirror 334 is moved in a direction perpendicular to its surface so that the path length of the rays indicated by arrows 329 is changed by the movement of the mirror 334 (to the position indicated at 334', for example). After reflection from the mirror 334, the rays indicated by arrows 329 are partially reflected from the semitransparent mirror 332 and combine with the transmitted portion of the rays indicated by arrows 328 to form the beam of rays indicated by the arrows 331. The portion of the beam of rays indicated by arrows 329 which is transmitted though semitransparent mirror 332 does not enter into operation of the apparatus and is not shown. It will be observed that the pathlength of the rays indicated by arrows 328 is constant while the pathlength of the rays indicated by arrows 329 is variable and the variation in this length is equal to twice the movement of mirror 334.

The rays indicated by arrows 331 are directed to a

photosensitive detector 337, which is in turn connected to a fringe counter 338.

As the mirror 334 is moved, the rays indicated by arrows 328 and 329 will alternately interfere and reinforce, thus producing alternate increases and decreases in the amplitude of the light striking the photosensitive detector 337. These so-called fringes produced by interference may be counted by the fringe counter 338 responsive to the amplitude of the output of the photosensitive detector 337. Each cyclic variation from maximum to minimum and return, or in other words, each fringe, will represent a movement of the mirror 334 equal to one-half wavelength of the light from the oscillator 321. The fringe counter thereby indicates directly the movement of mirror 334 in terms of half wavelengths of the light from oscillator 321. The wavelength of light from oscillator 321 will be known to a high degree of accuracy and the indication on the fringe counter 338 may thus be converted to any desired units of measure.

The above interferomertic apparatus utilizing a nonresonant light oscillator, as previously described, is particulaly advantageous in that it allows measurement of greater distances than apparatus utilized heretofore. The maximum distance which can be measured by such apparatus, that is, the maximum measurble movement of mirror 334, is limited by the fact that a light source has a finite width of spectral line, or in more general terms a finite bandwidth. In other words, the light from any source is composed of light of a number of frequencies. Thus, when the length of the path of the light is changed by a sufficient amount, portions of the light will begin to interfere where other portions reinforce, and vice versa; so that it eventually becomes impossible to detect the interference fringes due to overlap of interference rings and fringes from light of slightly different frequencies.

Obviously, the more narrow the bandwidth of the light utilized, the greater the distance that can be measured before this effect becomes troublesome and prevents further counting of fringes and measurement of distance thereby. Nonresonant light oscillators such as indicated at 321 have a very narrow bandwidth on the order of 10 megacycles or less and, accordingly, provide a maximum measurable distance considerably greater than heretofore possible.

As an example of the utility of increased accuracy of interferometric distance measurements, the possibility of ruling diffraction grating longer than the present 10-inch limit can be cited. A longer grating can resolve more closely spaced spectral lines.

From the foregoing explanation, it will be understood that the apparatus shown in FIG. 13 provides interferometric apparatus for the measurement of distance which is capable of measuring greater distances without sacrifice of accuracy than had been possible with interferometric apparatus using other sources of light.

Resonant light amplifier for generation of transient pulses

For particular applications it may be desired to operate resonant light amplifier apparatus to generate transient pulses of light energy. Such pulses will generally have the characteristics of the output of the previously described resonant light oscillator, namely narrow frequency bandwidth, near planarity of wave shape, etc. In addition, the transient pulses will have their energy concentrated in a very short time. This time period may be shorter than 10^{-8} seconds. The length of the pulse may, of course, be longer and is subject to control, as is the shape of the pulse to some extent, all as will later be explained. The intensity of the pulse will be considerably higher than light intensity obtained with comparable apparatus in steady state operation. The light amplifiers of either the resonant or nonresonant type can, of course, be operated in pulse fashion simply by pulsing the source of exciting energy such as the light excitation or the electrical discharge excitation. This type of pulse operation does not, however, achieve the full advantages of pulse operation. It is rather preferred that the light amplifier apparatus be maintained with the working medium activated so that under proper conditions sustained oscillation could be produced. By sustained oscillations it is meant that regeneration could take place which would produce self-sustaining oscillation even though for a very short length of time.

The activated working medium in such condition contains a substantial amount of energy due to the presence of atoms, ions, or molecules at a higher energy level which are capable of a transition to a lower energy level upon stimulation by electro-magnetic radiation of the proper frequency. This stored energy can be released in a short time interval and is of a much greater magnitude than the relatively small amount of energy which would be added to the working medium by the source of exciting energy during an equally short time interval (as in normal, continuous operation).

Several mechanisms may be utilized to control resonant light amplifier apparatus to achieve this type of pulse operation.

One way of achieving the above type of pulse operation is by changing the effective number of excess excited atoms by means of the Zeeman or Stark effect. This may be accomplished by producing a sudden change in the magnetic or electrical fields, respectively.

Pulse operation can also be achieved by suddenly changing the resonant frequency of the working medium by the Zeeman or Stark effect (by changing the magnetic or electrical field in the cavity, for instance).

Pulsing may also be achieved by the use of a shutter mechanism, preferably an electronic arrangement, such as a Kerr cell, to effectively attenuate the light in the closed path of the resonant light amplifier so that the losses are great enough to prevent self-sustained oscillation for certain conditions of the shutter.

It is noteworthy that the same effects outlined above for pulsing purposes may be used to rapidly alter the gain of a light amplifier used as an amplifier. In the non-linear region of operation, harmonics of the modulation frequency would be generated.

Suitable apparatus for pulsing a light amplifier to produce transient pulses by means of the Zeeman effect may be provided by placing a resonant light amplifier between two "Helmholz coils." A magnetic field can then be generated through the resonant light amplifier which can be controlled so that it may be reduced to zero in a time of the order of 10^{-8} seconds. Obviously, magnetic fields of rapidly changing magnitude might also be impressed through other means such as microwave waveguides or cavities.

The effect of the magnetic field is to split certain energy levels into several sub-levels and thus reduce the number of atoms which may take part in a transition at a given frequency. For example, if the upper energy level with which one is concerned is split by a magnetic field (as in the case of $Na(6P \rightarrow 4S)$), for example, the number of atoms whose transitions may be induced by a given light frequency may be reduced below that necessary for a self-sustaining oscillation.

A triggering action is, therefore, produced when the previously split levels are suddenly brought to the same energy by reduction of the magnetic field.

In the case of molecules, most molecules have a very small magnetic dipole moment in the ground electronic state. (One exception is [NO] with a $2\pi_{1/2}$ ground state and a promising transition in the ultra-violet.) Many excited molecular states do have an electronic magnetic moment and the Zeeman effect would be large. This is not the case, however, for the excited state of interest in the iodine molecule previously discussed. In the case of polar molecules, there is a large electric dipole moment, and in such cases the Stark effect can be used to trigger

a transient pulse. This is accomplished by a changing electric field.

The Zeeman or Stark effect can be utilized for producing transient pulses in a different manner by utilizing the shift of resonant frequency of the working medium which is occasioned by changing the magnetic or electric field, as the case may be. As the field is increased, the resonant frequency changes. Thus, a field of only 100 gauss may be used to detune the light amplifier to allow the excited state concentration to build up preparatory to the generation of a pulse upon collapse of the magnetic (or electric) field.

The detuning and tuning principle of pulsing may also be instrumented by changing the physical characteristics of the resonant light amplifier. For example, a metal surface may be deposited on a piezoelectric crystal to form a mirror reflector. If this is utilized as one of the reflectors in the resonant light amplifier and the mirrored surface is such that it can be electrically controlled to displace perpendicular to its surface, then the physical resonant frequency of the light amplifier can be changed. If the difference between resonant frequencies of the resonant light amplifier optical system is of the same order as the transition line, and if the resonance is tuned off one side of the line, then a sudden shift in tuning to the line center will trigger a transient pulse.

A further and particularly simple and effective means of generating transient pulses in a resonant light amplifier is shown in FIG. 15. In FIG. 15 a resonant light amplifier is shown comprising an enclosure 401, the interior 402 of which is filled with a suitable one of the working mediums previously described. In FIG. 15 the excitation means and reservoir are omitted for simplicity. Within the enclosure 401 there is a prism 403 similar to that shown in FIG. 5 and described with reference thereto. A window 404 is located at the opposite end of the enclosure 401. Another similar reflecting prism 405 is provided, and in the apparatus of FIG. 15 is shown outside the enclosure of 401. It will be understood that the reflecting prisms 403 and 405 can alternatively be either both within the enclosure or both outside the enclosure.

As explained in detail with reference to FIG. 5, the prisms 403 and 405 are arranged so that incident light rays indicated by arrows 408 strike their respective faces 406 and 407 at or near Brewster's angle for the prism and its environment. With this arrangement light of a particular polarity is transmitted through and internally reflected within the prism while light of other polarity is partially reflected externally from the respective faces 406 and 407. Thus, a low-loss closed path is provided only for a light of a particular polarity.

The apparatus of FIG. 15 differs functionally from the apparatus of FIG. 5 in that a Kerr cell 411 is placed in the closed light path so that all light traversing the closed path passes through the Kerr cell 411.

The Kerr cell is electrically energized from a pulse generator and timer 412. As will presently be seen, the Kerr cell controls the pulses of light output and, accordingly, the pulse generator and timer 412 will be designed to produce pulses of the proper duration and occurring at the desired time to produce light pulses of the characteristic desired in a particular application.

The construction of Kerr cells is well known and will not be explained in detail. It will suffice to say that in one form the Kerr cell comprises a number of conductive plates (preferably oriented at 45° to the plane of the paper in FIG. 15) connected as by leads 413 to a source of electrical potential such as the pulse generator and timer 412. The spaces between the conductive plates 414 is occupied by a dielectric (usually liquid) such that electrification of the plates 414 to produce an electric field in the dielectric causes a change in polarization of a plane polarized wave passing through the Kerr cell, as a result of the well known Kerr effect.

Prisms 415 are provided at the ends of the Kerr cell 411 so that the light rays indicated by the arrows 408 enter the Kerr cell at an angle substantially equal to Brewster's angle with both external and internal faces of the prism 415; this minimizes reflection from the faces of the prisms 415 and thus reduces the loss of light due to the introduction of the Kerr cell in the system.

It will be understood that since a nearly unattenuated closed path is provided for light of a particular polarity in FIG. 15 and that light of a different polarity is partially reflected out of the closed path, energization of the Kerr cell to produce a shift of polarization of the light passing therethrough will cause substantial loss of light energy on the closed path due to reflection from the faces 406 and 407 of the prisms 403 and 405, for example. The polarization can be changed by the Kerr cell in different manners: it can be changed to circular polarization, or it can be shifted through a new polarization angle at 90° to the original, or it can be otherwise changed. Any change in polarization will introduce attenuation of the light rays, the maximum attenuation being obtained by a 90° change in plane polarization angle.

Accordingly, when the Kerr cell 411 is energized losses of energy from the resonant light amplifier will prevent oscillation from building up even though an excess population exists in a higher energy level from which self-sustaining stimulated emission would occur due to transitions from a lower energy level if the conditions of energy conservation in the system were near optimum. Thus, if the Kerr cell under these conditions is suddenly deenergized to reduce the energy loss rate, the energy represented by the higher population in the upper energy level will be rapidly dissipated by regenerative stimulated emission, creating a pulse of light energy in the resonant light amplifier.

As in the case of the apparatus of FIG. 5, an output can be obtained from the light amplifier of FIG. 15 by rendering the face 407 of the prism 405 partially reflective. This can be done by the application of a partially reflected coating, or may alternatively be accomplished by rotating the prism 405 through an axis perpendicular to the paper so that the rays indicated by arrows 408 do not strike exactly at Brewster's angle but at a slightly different angle, thus resulting in partial reflection from the face 407 of the prism 405 and producing output rays indicated by arrows 409.

The apparatus shown in FIG. 15 and described above is particularly advantageous in that the Kerr cell is capable of actuation in time intervals as shown as 10^{-9} seconds.

It should be noted incidentally that the apparatus of FIG. 15 is suitable with a substitution of a proper modulating circuit for the pulse generator 412 for use as a very efficient modulator for a resonant light amplifier used either as an oscillator or an amplifier. Thus, the apparatus of FIG. 15 slightly modified may be utilized as an alternative form of oscillator in the transmitter of the communication system shown in FIG. 10.

The apparatus of FIG. 15 produces an output which in general has the same characteristics of the output of a nonresonant light amplifier, as in FIG. 5, for example. In addition, however, the output is capable of being pulsed with very short pulse times in FIG. 15. Also in the apparatus of FIG. 15 the peak pulse intensity is much higher than the intensity obtainable from the non-pulsed nonresonant light amplifier such as shown in FIG. 5. This increase in power results from the fact that substantial energy is stored in the interior 402 of the light amplifier enclosure 401 when the working medium therein is maintained at an excited state. This energy is releasable in a very short pulse by means of the Kerr cell 411 thus providing a very high peak power intensity.

Non-reflecting nonresonant light amplifier

In the discussion hereinabove, pulsed light amplifiers were discussed wherein a closed light path was provided by means of reflectors and the amplifier operated in ba-

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a transient pulse. This is accomplished by a changing electric field.

The Zeeman or Stark effect can be utilized for producing transient pulses in a different manner by utilizing the shift of resonant frequency of the working medium which is occasioned by changing the magnetic or electric field, as the case may be. As the field is increased, the resonant frequency changes. Thus, a field of only 100 gauss may be used to detune the light amplifier to allow the excited state concentration to build up preparatory to the generation of a pulse upon collapse of the magnetic (or electric) field.

The detuning and tuning principle of pulsing may also be instrumented by changing the physical characteristics of the resonant light amplifier. For example, a metal surface may be deposited on a piezoelectric crystal to form a mirror reflector. If this is utilized as one of the reflectors in the resonant light amplifier and the mirrored surface is such that it can be electrically controlled to displace perpendicular to its surface, then the physical resonant frequency of the light amplifier can be changed. If the difference between resonant frequencies of the resonant light amplifier optical system is of the same order as the transition line, and if the resonance is tuned off one side of the line, then a sudden shift in tuning to the line center will trigger a transient pulse.

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The construction of Kerr cells is well known and will not be explained in detail. It will suffice to say that in one form the Kerr cell comprises a number of conductive plates (preferably oriented at 45° to the plane of the paper in FIG. 15) connected as by leads 413 to a source of electrical potential such as the pulse generator and timer 412. The spaces between the conductive plates 414 is occupied by a dielectric (usually liquid) such that electrification of the plates 414 to produce an electric field in the dielectric causes a change in polarization of a plane polarized wave passing through the Kerr cell, as a result of the well known Kerr effect.

Prisms 415 are provided at the ends of the Kerr cell 411 so that the light rays indicated by the arrows 408 enter the Kerr cell at an angle substantially equal to Brewster's angle with both external and internal faces of the prism 415; this minimizes reflection from the faces of the prisms 415 and thus reduces the loss of light due to the introduction of the Kerr cell in the system.

It will be understood that since a nearly unattenuated closed path is provided for light of a particular polarity in FIG. 15 and that light of a different polarity is partially reflected out of the closed path, energization of the Kerr cell to produce a shift of polarization of the light passing therethrough will cause substantial loss of light energy on the closed path due to reflection from the faces 406 and 407 of the prisms 403 and 405, for example. The polarization can be changed by the Kerr cell in different manners; it can be changed to circular polarization, or it can be shifted through a new polarization angle at 90° to the original, or it can be otherwise changed. Any change in polarization will introduce attenuation of the light rays, the maximum attenuation being obtained by a 90° change in plane polarization angle.

Accordingly, when the Kerr cell 411 is energized losses of energy from the resonant light amplifier will prevent oscillation from building up even though an excess population exists in a higher energy level from which self-sustaining stimulated emission would occur due to transitions from a lower energy level if the conditions of energy conservation in the system were near optimum. Thus, if the Kerr cell under these conditions is suddenly deenergized to reduce the energy loss rate, the energy represented by the higher population in the upper energy level will be rapidly dissipated by regenerative stimulated emission, creating a pulse of light energy in the resonant light amplifier.

As in the case of the apparatus of FIG. 5, an output can be obtained from the light amplifier of FIG. 15 by rendering the face 407 of the prism 405 partially reflective. This can be done by the application of a partially reflected coating, or may alternatively be accomplished by rotating the prism 405 through an axis perpendicular to the paper so that the rays indicated by arrows 408 do not strike exactly at Brewster's angle but at a slightly different angle, thus resulting in partial reflection from the face 407 of the prism 405 and producing output rays indicated by arrows 409.

The apparatus shown in FIG. 15 and described above is particularly advantageous in that the Kerr cell is capable of actuation in time intervals as shown as 10^{-9} seconds.

It should be noted incidentally that the apparatus of FIG. 15 is suitable with a substitution of a proper modulating circuit for the pulse generator 412 for use as a very efficient modulator for a resonant light amplifier used either as an oscillator or an amplifier. Thus, the apparatus of FIG. 15 slightly modified may be utilized as an alternative form of oscillator in the transmitter of the communication system shown in FIG. 10.

The apparatus of FIG. 15 produces an output which in general has the same characteristics of the output of a nonresonant light amplifier, as in FIG. 5, for example. In addition, however, the output is capable of being pulsed with very short pulse times in FIG. 15. Also in the apparatus of FIG. 15 the peak pulse intensity is much higher than the intensity obtainable from the non-pulsed nonresonant light amplifier such as shown in FIG. 5. This increase in power results from the fact that substantial energy is stored in the interior 402 of the light amplifier enclosure 401 when the working medium therein is maintained at an excited state. This energy is releasable in a very short pulse by means of the Kerr cell 411 thus providing a very high peak power intensity.

Non-reflecting nonresonant light amplifier

In the discussion hereinabove, pulsed light amplifiers were discussed wherein a closed light path was provided by means of reflectors and the amplifier operated in ba-

sically the same fashion except that short time pulse operation was created, as by means of the Kerr cell in FIG. 15, for example.

In the previously explained operation of light amplifier devices, the stimulated emission added coherently to the inducing radiation. Except for the refraction effects, a wave-train traveling through an activated light amplifier medium is linearly amplified as long as the density of excited atoms (or ions or molecules) remains substantially unchanged and provided the transition is not "power broadened." By means of operation outside the above limits, different effects are produced (e.g. non-linear amplification), and apparatus utilizing these effects has capabilities beyond those of the previously discussed light amplifier devices.

Apparatus for producing light pulses by the utilization of light amplification in a light amplifier with non-reflecting walls is shown in FIG. 16. A pulsed resonant light amplifier is indicated schematically at 421. This amplifier may be constructed in accordance with previously described principles, for example, in accordance with FIG. 15 and the description thereof.

The pulsed resonant light amplifier 421 is controlled by a pulse generator and timing circuit 422 as previously explained in connection with FIG. 15.

The output from the pulsed resonant light amplifier 421 is in the form of light pulses indicated by arrows 423. These light pulses are directed as desired such as by the lens 424.

In order to take maximum advantage of the amplification effect in a non-reflecting, nonresonant light amplifier according to the present invention, it may be desired to provide the non-reflecting amplifier with a light pulse having as short a rise time as possible. Otherwise, some of the energy stored in the non-reflecting amplifier will be expended in amplification of the low intensity leading portion of the input pulse.

Accordingly, a very high speed shutter arrangement is illustrated in FIG. 16 for obtaining a pulse output having a very short rise time. Whereas the rise time of the pulsed resonant light amplifier 421 may be on the order of 10^{-8} seconds, the shutter 425 may be constructed to have an output having a rise time on the order of 10^{-11} seconds.

A shutter 425 comprises a mirror 426 which is very rapidly rotated about an axis indicated at 427. An opaque member 428 is provided having a narrow slit 430. For the position of the mirror 426 shown in FIG. 16, the rays 423 from the pulsed resonant light amplifier 421 are focused on the slit 430 and accordingly pass through the opaque member 428. As the mirror 426 is rotated, the rays from the amplifier 421 are swept across the opaque member 428 and periodically, for a very short time interval, pass through the slit 430.

The width of the slit 430 is preferably that of the width of the Fraunhofer pattern for the light beam at that particular point. The width of the Fraunhofer pattern will be greater as the distance of the opaque member 428 from the mirror 426 is increased. This distance may be set at any convenient value and, if desired, the path of the light rays 423 may be folded by the use of mirrors or the like in order to make the shutter apparatus of manageable size. For example, if the opaque member 428 is placed 10 meters away, the width of the Fraunhofer pattern will be approximately $\frac{1}{10}$ of 1 millimeter. The cutting of a slit of this width in the opaque material 428 presents no difficulties.

The mirror 426 is preferably rotated at a very high speed to obtain a pulse having a very short rise time from the shutter 425. If the velocity can be raised to 10^6 radians per second, a pulse of approximately 10^{-11} seconds can be obtained. Known techniques for obtaining high rotational velocity can be utilized in the construction of the rapidly rotating mirror 426. For example, the mirror can comprise a ground "flat" on a small metal cylinder and can be placed in an evacuated enclosure and provided with a substantially frictionless suspension. If desired, magnetic suspension can be utilized. The mirror may be brought to a high rotational velocity by a rotating magnetic field.

It will be understood that the particular shutter arrangement described with reference to FIG. 16 is a preferred form which is capable of attaining a very short rise time for the output pulse from the shutter. The operation of the nonresonant non-reflecting light amplifier of FIG. 16 is not limited to use with such extremely high speed shutters. Thus, in many instances a slower and relatively simpler shutter such as a Kerr cell may be used to provide a light pulse to the non-reflecting amplifier tube. Furthermore, although a resonant light amplifier provides a desirable type of light source for pulsing the non-linear light amplifier tube, any other light source of appropriate frequency could be utilized if controlled to give appropriate short duration light pulses.

The light on the shutter 425 is directed as by means of a lens 429 into a non-reflecting light amplifier tube 431. The amplifier tube 431 comprises a closure 432 having an input window 433 and an output window 434. The interior 435 of the non-reflecting light amplifier tube is filled with a suitable working medium. When utilized in conjunction with a pulsed resonant light amplifier 421, the working medium of the non-reflecting light amplifier tube 431 will generally be the same as that of the pulsed resonant light amplifier 421. In any case, the working medium of the amplifier tube 431 will be such that it is stimulated by the exciting light introduced through the input window 433.

The output from the non-reflecting light amplifier tube 431 is projected out through the output window 434.

The nonresonant non-reflecting light amplifier apparatus of FIG. 16 operates as follows.

The operation of the pulsed resonant light amplifier 421 and of the shutter 425 have previously been explained. It should be noted that the shutter 425 should be synchronized with the pulse of the pulsed resonant light amplifier 421 so that the open condition of the shutter 425 occurs as nearly as possible to the maximum intensity of the light pulse from the pulsed resonant light amplifier 421. This function is accomplished by the pulse generator and timing circuits 422.

Light pulses from the shutter 425 pass through the lens 429 where they are collimated. The collimated light pulse passes into the non-reflecting light amplifier tube 431 through the input window 433. In FIG. 16 the excitation means for the non-reflecting light amplifier tube 431 is omitted for simplicity. It will be understood that the working medium in the interior 435 of the amplifier tube 431 will be excited so that there is an excess population of atoms, ions, or molecules in an upper one of two energy levels separated by the frequency of the stimulating light from the pulsed resonant light amplifier 421. The activation energy for the working medium in the light amplifier tube 431 may be provided by light energy introduced through the wall 432, by an internal discharge, or by any other means such as those described hereinbefore.

It will be noted that reflection means are not included within the light amplifier tube 431 as they were in previous light amplifiers explained hereinabove. Accordingly, light photons emitted within the light amplifier tube 431 are not normally reflected to retraverse the interior 435 of the light amplifier tube 431. Usually a photon emitted will thus traverse less than the length of the light amplifier tube before being transmitted to the exterior or absorbed.

Accordingly, there is little opportunity for regenerative action within the light amplifier tube, and a considerable excess population of atoms (or ions or molecules) in the upper two energy levels can be achieved and main-

tained without spontaneous regenerative oscillation in the light amplifier tube.

When this condition exists in the light amplifier tube 431, it is conditioned to act as an amplifier. Such a non-reflecting nonresonant light amplifier is capable of amplifying light with a frequency bandwidth smaller than the corresponding transition bandwidth of the atoms, ions, or molecules of the working medium, but larger than the resonance response bandwidth of a resonant light amplifier. Also, wave-trains with non-planar wave fronts may be coherently amplified. For example, a diverging spherical wave may be amplified without changing its shape. Such a wave would not be accepted by a resonant light amplifier with planar specular reflectors. Of course, a resonant light amplifier may be constructed with reflectors of other than plane shape for amplifying non-planar waves. However, the more flexible non-reflecting nonresonant amplifier is preferred for this purpose.

Although the light amplifier tube 431 would operate as a substantially linear amplifier for low intensity light inputs, it is of more interest to consider the operation of the apparatus for relatively high intensity input pulses. By relatively high intensity, it is meant that the pulse intensity is sufficient to substantially depopulate the higher energy level at a given point before the entire pulse wave-train passes this point in the light amplifier tube. Under such conditions it will be apparent that while the first portion of the input wave-train of light will be amplified to a substantial extent, the trailing portion of the wave-train will not be amplified or will be only slightly amplified.

As the pulse passes through the light amplifier tube 431, this effect will be highly cumulative for as the intensity of the leading portion of the wave-train is built up it will tend to more completely and more rapidly depopulate the upper energy level in the volume through which it passes so that there will be effectively an exponential growth of the intensity of the leading portion of the pulse together with a generally corresponding shortening of the pulse due to the lack of amplification of the trailing portion of the pulse wave-train.

From the foregoing explanation, it will be seen that the non-reflecting light amplifier tube 431 produces a great intensification of the input pulse, together with a considerable shortening of the pulse length. The shortening of the pulse length which can be obtained is limited by the fact that the Fourier transform of a short pulse contains frequency components far removed from the nominal frequency. Thus, as the pulse becomes shorter and shorter, the energy in the pulse will cease to be concentrated at the nominal frequency; as a result the efficiency of the process will deteriorate, thus limiting the shortening of the pulse which can be obtained. Due to this effect and for other reasons, it is unlikely that a pulse length shorter than several hundred cycles of the light frequency can be obtained, no matter how long the non-reflecting amplifier tube is made.

It should be noted that the operation of the non-reflecting light amplifier tube comes somewhat more complex when the transition becomes "power broadened." These different effects are of consequence when the time required for the wave-train length to pass a given point is less than the phase relaxation time The various effects produced under this condition will not be discussed in detail. It will suffice to say that under these conditions the pulse passing through the non-linear light amplifier tube will continue to grow shorter and denser. One minor effect is that the peaking action on the input wave form will be somewhat delayed so that the peak will be formed somewhat behind the leading edge of the input pulse wave-train.

Short light pulses such as those obtained from the pulsed resonant light amplifier and even shorter pulses obtainable from the non-reflecting light amplifier tube are useful for various purposes and in various systems, some of which will later be explained in some detail.

The apparatus of FIG. 16 by itself would be useful in the field of high speed photography. The length of pulse obtainable with apparatus as shown in FIG. 16 may be as short as the order of 10^{-12} seconds. The ability of a pulse of this short length to "stop" action can be appreciated by the fact than an object traveling at the speed of light would be stopped within one millimeter by such a short pulse of light.

Although the total amount of light energy may be somewhat smaller than conventional photographic light sources, this would not be a serious limitation, and particularly so in the field of microphotography, for example, where only a small area need be illuminated. The fact that the output from the non-linear light amplifier has very nearly plane waves makes it possible to focus the output to as small an area, as would be desired for microphotographic purposes.

Light energy machining apparatus

A system is shown in FIG. 17 including light powered machining apparatus together with control means for highly accurate control of the machining apparatus. The light powered machining apparatus will desirably include either a pulsed resonant light amplifier or a nonresonant pulsed light amplifier as discussed above (or both).

The characteristic of the output from resonant light amplifiers as previously described, namely that the light energy output constitutes nearly planar waves, makes it possible to focus the output in a very small spot, as previously explained. The area of the focusing spot may approach one square wave length under ideal conditions. The heating effect of such an intensely focused beam of energy is such that ordinary materials and even highly heat-resistant materials will be virtually instantaneously vaporized and/or disassociated when placed at the focus of the beam. Thus, a highly efficient and heretofore unequalled cutting and machining instrument may be provided by the use of focused light from a resonant light amplifier. The operability of the machining apparatus does not depend upon the ability to focus the beam to a spot approaching only one square wave length in area. The apparatus will be highly effective even though the focal spot is much larger.

The heating power for the machining apparatus of FIG. 17 is provided by a pulsed light amplifier 441. The output beam from the pulsed light amplifier 441 is indicated by arrows 443 which are directed by a mirror 442 to a converging lens 444. The means for directing and converging the beam, are of course, merely illustrative and other means such as a parabolic mirror could alternatively be utilized.

The beam indicated by arrows 443 is controllably directed by a rotatable mirror 445. The mirror 445 is pivoted to rotate about an axis perpendicular to the plane of the paper indicated at 446 and is also pivoted to rotate about the axis of a shaft 447. The shaft 447 is rotated by a motor 448. The mirror 445 is also motivated to oscillate about the axis 446 by suitable motive means which have been omitted for simplicity in the schematic diagram of FIG. 17. A workpiece is placed in the path of the beam indicated by arrows 443, the workpiece being illustrated as a flat plate 449 in FIG. 17, although the nature of the workpiece upon which the machining is to be performed is obviously not limited to such flat material.

The workpiece 449 is located so that the focal point 451 of the beam 443 strikes the workpiece. Accordingly, the workpiece 449 will be etched or cut through due to evaporation of the material by the beam 443. A cut in the workpiece 449 is indicated at 452. The portion of the workpiece 449 which is cut or etched will be controlled by the control circuit 453 which controls the pulsing of the light amplifier 441. The pulsed light amplifier 441 may be con-

trolled to produce single pulses under control of the control circuit 453, but it will generally be more efficient to produce a series of pulses in order to remove material from the desired area of the workpiece at a high rate of speed.

It should be noted that a continuously operating resonant light amplifier could be used in place of the pulsed light amplifier 441 but the latter is preferred from the point of view of efficiency and effectiveness.

To control the cutting operation performed with the energy supplied by the pulsed light amplifier 441, it is desirable to utilize a control system also incorporating a resonant light oscillator. The use of a resonant light oscillator in the control system for the machining operation provides a light probe for scanning a template which has a resolution comparable to the resolution of the cutting beam itself. It is possible, however, to utilize any other suitable control system for the cutting apparatus previously described.

The control system of FIG. 17 comprises a light oscillator 454, the output beam of which is indicated by arrows 456. It is not necessary for oscillator 454 to be pulsed, but it could be so operated if desired. The beam is directed by means of a partially reflecting mirror 455 so that a portion 457 of the beam 456 passes through a converging lens 458. The beam 457 is controllably directed by means of a rotating mirror 459 pivotally mounted about an axis 461 and on a rotatable shaft 462, which is rotated by a motor 463, all in a fashion similar to that previously described with respect to the apparatus for controlling the cutting beam.

The motor 463 for controlling the light probe of the control system is synchronized with a motor 448 controlling the cutting beam 443, although the motors need not necessarily be arranged to run at the same speed as it may be desired to have the scale of the pattern cut on the workpiece 449 either larger or smaller than the control pattern. The movements of mirrors 445 and 459 about axes 446 and 461 are also synchronized. The beam 457 is directed on a reflecting template 464, the focal point 465 of the beam falling approximately on the surface of the template. The template 464 may comprise a dark line drawn on a reflecting surface or vice versa.

Light is reflected from the template 464 back to the mirror 459 and through the lens 458 and through the partially reflecting and partially transparent mirror 455 to a converging lens 466 where it is directed on the sensitive surface of a photodetector 467.

As the mirror 459 is rotated by the motor 463 and oscillated about the pivot 461, it will scan the reflecting template 464. Whenever a mark on the template 464 is traversed by the focal point 465, a sharp change in the intensity of the reflected light to the photodetector 467 will be produced. The output of the photodetector 467 is supplied to the control circuit 453. The control circuit 453 is arranged to operate the pulsed light amplifier in response to a decrease in reflected light intensity caused by the passage of the focal point 465 over a dark line on the template 464. Alternatively, the control circuit could be arranged to detect changes in light intensity or to respond to increased light intensity or to respond in any other desired manner to the characteristics of a template.

From the foregoing explanation, it will be seen that machining apparatus of a novel type having capabilities beyond those of previously known apparatus is provided by the above-described apparatus. It will be obvious that the principles explained by the simple example of FIG. 17 may be extended to machining operations in three dimensions.

The control system of FIG. 17 could obviously also be modified to incorporate servo control or "feedback" control to cause the sensing light beam to follow a line or edge of the template. By such an automatic feedback control, the beam could also be kept fixed on a reflecting point on a moving object. By means of such a servo controlled sensing system, and a suitable control circuit, the motion of a moving object, such as a machine tool, may be controlled.

Alternatively, the position or orientation of an apparatus with respect to the moving object may be controlled. Thus, any type of tool, such as the pulsed light tool illustrated in FIG. 17, for example, could be positioned in correspondence with the motion of the workpiece, or a moving template or any other moving object.

It is clear that the light beam from a resonant light amplifier provides a highly accurate and flexible probe for sensing the positions of a great variety of objects and thereby provides the means for a correspondingly accurate automatic control of apparatus.

Another illustration of the use of a pulsed light amplifier for a machining operation is shown in FIG. 18. A pulsed light amplifier 471 is shown schematically having an output beam 472 which is focused by a converging lens 473. The beam 472 is focused at a point 474 on the surface of a rotating workpiece 475.

In order to dispose of the debris from the evaporation process, a gas blast is provided from a nozzle 476. The light source and associated equipment is protected by a transparent shield comprising a transparent plate 478 rotated about the axis of a shaft 479 by a motor 481.

The transparent plate 478 is itself protected by a liquid stream provided from a conduit 482. The liquid is preferably transparent and may, for example, be water.

The liquid flow onto the rotating plate 478 will spread out in a thin film due to centrifugal force, and being transparent, will not interfere with the transmission of the light beam through the transparent plate 478 and onto the workpiece 475.

FIG. 18 illustrates one of the possible variations in the use of the pulse light amplifier as a cutting or machining device. In addition, techniques utilized in machining operations in general are applicable to the above-described apparatus utilizing light energy for cutting and machining.

Apparatus similar to that shown in FIG. 18 may be in part enclosed in a vacuum-tight envelope for the purpose of evaporating material to be condensed on another object; that object could be a mirror, for example.

Light oscillating heating apparatus

In FIGURE 11, heating apparatus is shown utilizing a resonant light oscillator 261 having a suitable power source 262. As previously explained, the output of such an oscillator produces a beam of very nearly plane light waves, that is, their convergence or divergence is exceedingly small.

As a consequence of this characteristic of the output of resonant light oscillator, the beam is capable of being focused to a very fine point. In FIGURE 11 the output beam 263 is focused by means of mirror 264 on a target 266. Apparatus may be provided for maintaining a target in the focal spot, particularly in the event that the target is a liquid or gas.

Light energy in or near the visible spectrum has been utilized to produce high temperatures in previously known apparatus. For example, light from the sun has been used in conjunction with focusing mirrors to produce a high temperature heat source for research purposes. Although a large quantity of heat can be produced in this manner, the area within which it may be focused remains relatively large due to the large angle subtended by the sum.

Another approach to produce a high temperature by focusing light energy involves the use of a near-point-source of energy such as an electrical arc between carbon electrodes, for example. Such an approach is also limited by the fact that the so-called point source of energy is of fihite extent and generally must be increased in size as greater power outputs are produced. It can be shown from the second law of thermodynamics that an object

heated by incoherent radiation cannot become hotter than the source of the radiation.

The resonant light oscillator produces a coherent beam which is divergent only by an amount on the order of one (1) part in 10^5; and thus is capable of being focused within an extremely small volume. Such a beam could be focused at nearby distances on a spot having an area on the order of one (1) wavelength squared. At greater distances the smallness of the focused spot is limited to the size of the Fraunhofer diffraction pattern. The energy intensity obtainable with moderate amounts of power by such apparatus is greatly in excess of any previously obtained radiation intensity. Such apparatus has obvious application both for research and in practical applications.

In some applications this type of heating by focusing the light oscillator beam into a small intense spot has unique advantages. For example, it is often desirable to produce chemical reactions which must be produced at high temperatures; in such cases it is sometimes desirable that after being heated to a high temperature, that the material being processed thereafter be rapidly lowered in temperature. An example of such a reaction is the reaction between nitrogen and hydrogen, $N_2+3H_2 \rightarrow 2NH_3$. This reaction can be promoted at a high temperature, but if the reaction product is allowed to cool slowly it will disassociate and revert to the original components thus achieving its low temperature equilibrium condition. Utilizing the apparatus of FIGURE 11 however, it is possible to move the reactants in and out of the volume wherein the heating is concentrated very rapidly thus raising the reactants to high temperature and cooling it rapidly and thereby causing it to remain in its high temperature equilibrium state producing the desired compound.

Obviously the apparatus of FIGURE 11 may also be utilized to produce the disassociation of materials through the creation of very high temperatures.

Certain high temperature reactions which may be induced by use of the heating apparatus of FIGURE 11 are exothermic, that is, they result in the production of heat energy. Thus in some instances the heating apparatus of FIGURE 11 may be utilized for the production of energy in the form of heat as well as for creating useful products of chemical reactions. An example of an exothermic reaction taking place at high temperature is the combination of aluminum and oxygen to produce Al_2O_3. A useful product of this reaction is synthetic sapphires.

An alternative form of apparatus for concentrating light energy for the purpose of heating or for other useful purposes is shown in FIGURE 19. The apparatus shown in FIG. 19 is particularly adapted to the concentration of light energy on a liquid target material and is shown in somewhat more detail than the schematic showing of heating apparatus in FIGURE 11. The apparatus of FIGURE 19 will be explained as it is utilized for the production of X-rays by subjection of a liquid material to high temperature and high light intensity. It will be understood however that this apparatus is also susceptible of use for promoting reactions to obtain useful products or to obtain heat energy.

The apparatus of FIGURE 19 comprises a light oscillator **501** having an output beam of light indicated by arrows **503**. The oscillator **501** may be of a resonant type, thus having an output which is comprised of nearly planar waves which can be focused into an exceedingly small volume and accordingly provide a high intensity. In some instances it may be preferred to use a pulsed resonant light oscillator for the oscillator **501**. This allows a still higher energy intensity to be obtained by reason of the concentration of energy in short pulses, as was explained in the explanation of the pulsed light amplifiers and oscillators. A still higher intensity may be obtained by using a pulsed nonresonant amplifier in conjunction with a pulsed resonant oscillator as explained in the discussion of FIGURE 16.

The output from the light oscillator **501** is concentrated by a lens **502**. Obviously a mirror may be used rather than the lens **502** for the concentration of the light beam if desired.

An enclosure **504** is provided within which the light beam is concentrated. A window **505** is provided in the enclosure for entrance of the light beam. A protective shield is provided for the window **505** comprising a rotatable transparent member **506** which is mounted on a shaft **507** and rotated thereupon by motive means not shown.

The shield **506** is provided with a protective film of non-volatile liquid from a conduit **508**. The film of liquid prevents damage to the shield **506** which would degrade its transmissivity and at the same time the film of liquid is transparent to the light beam.

The interior of the enclosure **504** is substantially evacuated by a vacuum pump **509**. Accordingly the energy of the light beam can be concentrated and dissipated almost entirely in the liquid target rather than being partially dissipated by an atmosphere within the enclosure **504**. The target for the production of X-rays by excitation by the light beam **503** may comprise gallium, mercury or any other suitable X-ray emitting material. In FIGURE 19 the liquid is illustratively represented as mercury.

A quantity of mercury **511** is pumped through a conduit **516** by a pump **515** where it is cast upon a rotating disk **512**. The disk **512** is rotated on a shaft **513** by means of a motor **514**. The mercury is spread into a thin sheet by the centripetal force due to the rotation of the disk **512**. The mercury is projected from the edge of the disk still in a sheet **517** so that the focal point **518** of the light beam **503** strikes substantially on the projected sheet of mercury **517**.

X-rays indicated by arrows **519** are produced by excitation of electrons from the lowest levels of the atoms or ions of the target substance (Hg in FIG. 19) either directly by the photons of light or by creation of high temperatures with resulting particle collisions.

The X-rays may be produced within a very small volume yielding a near point source. The more nearly the source approaches a point source the higher the resolution which is possible in X-ray photography and other applications of the X-rays produced.

The arrangement shown in FIGURE 19 provides a liquid target at the focal point of the light beam which is not supported by physical structure. The problem of damage of physical structure by close proximity of the focal of the light beam is thereby further reduced. Furthermore, the mercury surface presented at the focal point of the light beam is rapidly moving and continuously refreshed so that mercury particles which have been excited by the light beam with resulting vaporization, disassociation or impartation of high velocity are replaced by a new mercury surface which provides a suitable target for the concentrated light beam.

As previously explained the apparatus of FIGURE 19 may readily be adapted for processes other than the production of X-rays. For example other types of radiation may be produced or other types of reactions may be promoted as previously explained in connection with FIGURE 11.

Although the apparatus of FIGURE 19 is shown and described as particularly adapted to excitation of a liquid target material, it is obvious that a gaseous target material could be utilized by simply replacing the means for projecting a liquid sheet by a suitable means for projecting a gaseous stream, such as a nozzle, or by filling the whole of chamber **504** with a suitable gas (e.g., xenon). It should also be noted that the target material need not be a single element or substance by may comprise a combination of elements or substances which are to take part in a reaction promoted by the exciting light beam.

From the foregoing it will be seen that the apparatus of FIGURE 11 and of FIGURE 19 and apparatus uti-

lizing similar principles is particularly adapted for the creation of high temperatures generally in a very small volume in order to promote reactions of various types to produce particular reaction products, to produce energy from the target material, or to convert the light energy into X-ray radiation or other higher frequency forms of radiation.

From the preceding detailed description of applicant's invention with its various features, it will be seen that light amplifier apparatus and systems incorporating such apparatus are provided which are useful for widely diversified purposes which provide advantages in the fields of communication, distance measurement, time measurement, and production of high temperatures, to name a few, which have heretofore not been possible to achieve. In addition to the variations and modifications to applicant's disclosed apparatus which have been suggested, many other variations and modifications will be apparent to those skilled in the art and, accordingly, the scope of applicant's invention is not to be construed to be limited to the particular embodiments shown or suggested but is rather to be limited solely by the appended claims.

What is claimed is:

1. Apparatus for generating radiation of higher frequency than that of light, comprising a light generator for generating nearly planar light waves, for focusing said light waves into a small volume, means for maintaining a liquid substance in the path of said light waves comprising a quantity of liquid, means for continuously supplying a volume of said liquid not directly supported by a solid structure to said small volume thereby causing an excitation of the innermost electrons of the atoms of said substance and converting a substantial amount of the light energy to higher frequency radiation.

2. Apparatus as claimed in claim 1 wherein the means for supplying a volume of liquid comprises a disk, means for rotating said disk and means for flowing said liquid on said disk to be thrown from said disk by centrifugal force in a substantially continuous sheet.

3. Apparatus as claimed in claim 2 further including a gas-tight housing surrounding said means for supplying a volume of liquid and means for substantially evacuating said housing.

No references cited.

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Feb. 25, 1969 J. W. EERKENS 3,430,046

COHERENT GAMMA RAY EMITTER

Filed June 23, 1966 Sheet 1 of 2

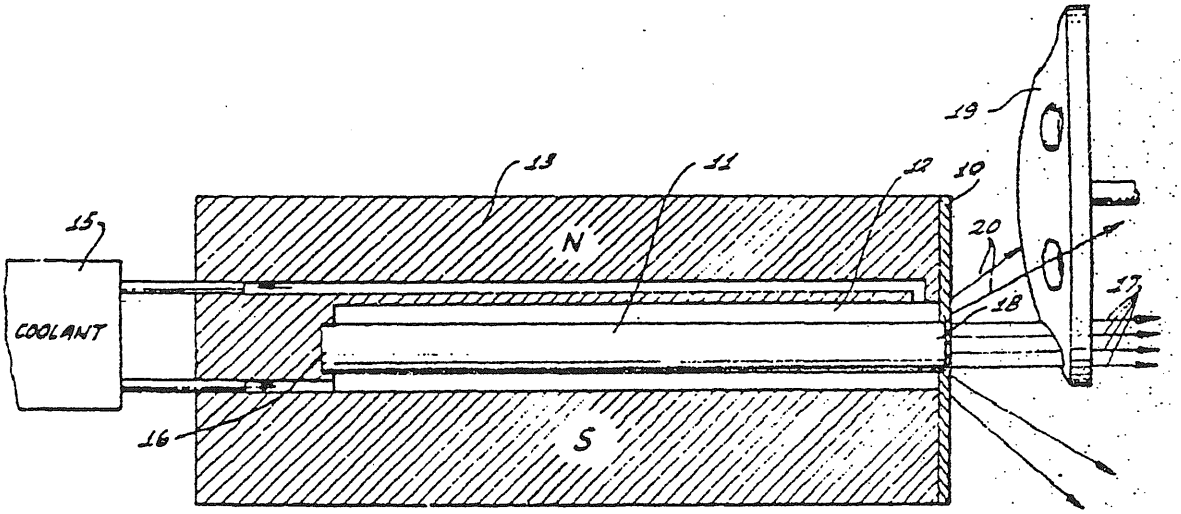
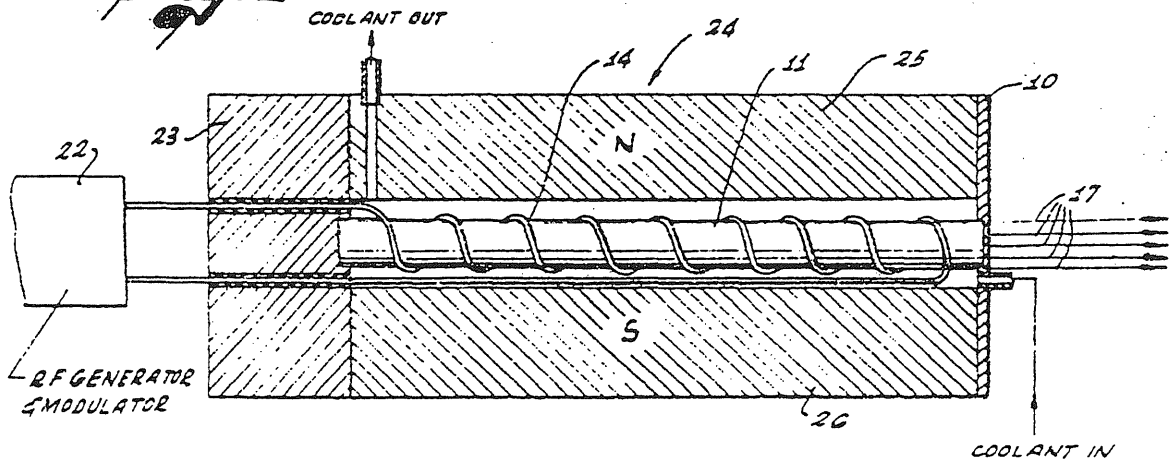


Fig. 1

Fig. 2



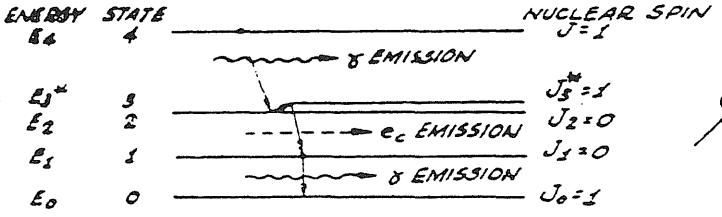


Fig. 3

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COHERENT GAMMA RAY EMITTER

Filed June 23, 1966 Sheet 2 of 2

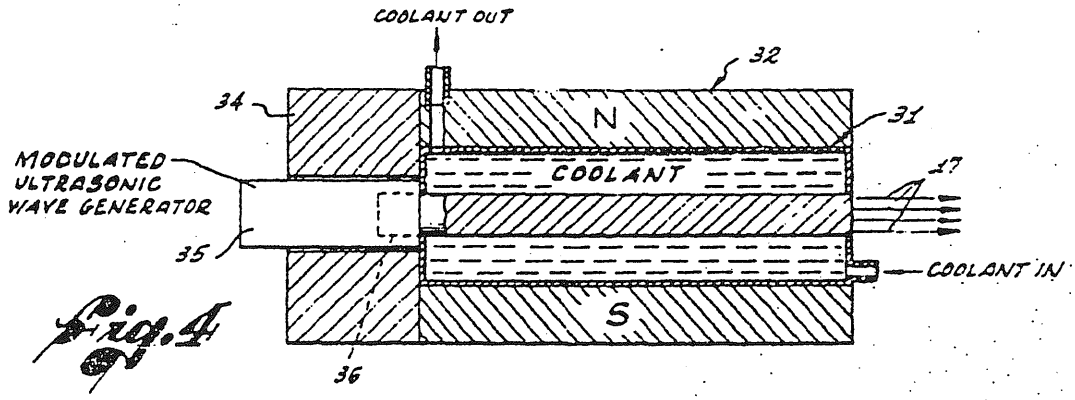


Fig. 4

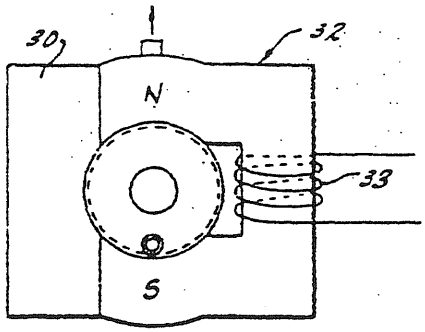
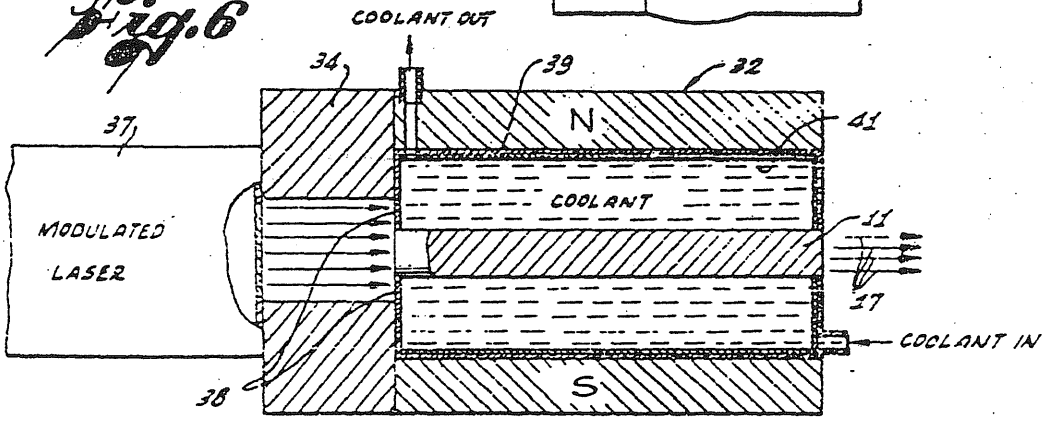


Fig. 5

Fig. 6



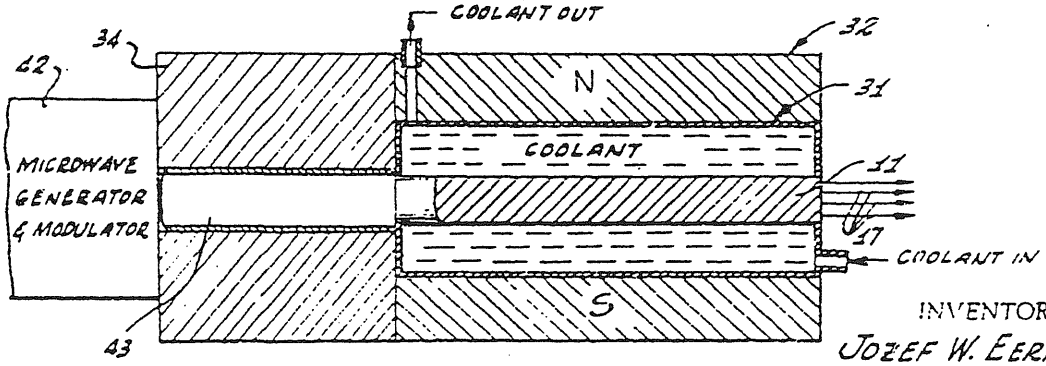


Fig. 7

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3,430,046

COHERENT GAMMA RAY EMITTER

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Continuation-in-part of application Ser. No. 196,282, May 21, 1962. This application June 23, 1966, Ser. No. 559,862

U.S. Cl. 250—84 15 Claims

Int. Cl. H01j 39/12

ABSTRACT OF THE DISCLOSURE

An emitter for coherent gamma rays comprising an elongated rod of a length-to-diameter ratio in excess of five and preferably between ten and twenty, containing a radioactive-isotope of the Mossbauer type. The rod is cooled below the temperature above which the Mossbauer effect therein is substantially suppressed to secure a stimulated emission of gamma rays within the rod and progressive multiplication of gamma rays along the axis of the rod to emit substantially superradiant, directionally coherent gamma rays from an end of the rod. An oscillating magnetic field may be applied axially of the rod at a radio frequency to bring the interaction between an excited nucleus and a conversion electron into substantial resonance to enhance the deexcitation rate between energy states of the excited nucleus and to introduce at least radio frequency time coherence into the emitted gamma ray beam. Means is disclosed to apply a steady magnetic field transversely to the axis of the rod to orient the nuclei of the radioisotope and cause the gamma rays to be emitted in preferred directions perpendicular to the direction of the field thereby securing a gain in directional coherence of the emission along the axis of the rod. Instead of the oscillating magnetic field the decay rate of the radioisotope may be controlled by the application of monochromatic ultrasonic waves or an electromagnetic beam of a wavelength to bring the internal conversion process of excited nuclei into a resonant condition, the electromagnetic beam being generated by a laser or a microwave generator. Modulation of the various control means for the decay rate of the radioisotope effects modulation of the emitted gamma ray beam.

This application is a continuation-in-part of application Ser. No. 196,282, filed May 21, 1962 for Coherent Gamma Ray Emitter, now abandoned.

The present invention relates generally to devices for emitting a beam of gamma rays from radioisotopes by the stimulated emission of gamma rays from radioactive nuclei, that is by nuclear maser action, and more particularly to such a device in which the beam is at least partially coherent and is controllable and modulatable.

A directionally coherent and partially phase coherent beam of gamma rays, known as a superradiant beam of gammas, may be secured from a rod of radioactive gamma ray emitting material in which there is stimulated emission of gamma rays from radioactive nuclei in a manner analogous to the stimulated emission of excited photons in lasers. The gamma ray emitting material is a radioactive isotope in the form of a long thin rod having a length to diameter ratio of at least 5 and preferably greater, in order to secure appreciable stimulated emission of gamma rays of coherent form. The L/D ratio of 5 is not a critical lower value but is a practical one below which the coherent gamma ray emission is not considered significant. There is no upper limit to the L/D ratio, a value of 40 or more being theoretically desirable, but for practical purposes it has been found that a ratio between 10 and 20 is desirable to secure significant coherent gamma ray emission with dimensions which may be handled from the standpoint of practicality and economy. Specific examples are rods 4 millimeters in diameter and 50 millimeters long, and 1 millimeter in diameter and 20 millimeters long. To secure a coherent or superradiant beam of gamma rays by stimulated emission from excited nuclei it is necessary that the frequency of the emitted gamma rays be monochromatic so that they fall within the resonance width of the excited nuclei and this occurs in gamma emitting radioisotopes of the class known as Mossbauer-effect radioisotopes, or simply Mossbauer radioisotopes of which examples are Co-57 (Fe-57), Sm-119 (Sm-119m), Os-191 (Ir-191), Ta-182 (W-182), Tm-171 (Yb-171), Co-60 (Co-60m), Kr-85 (Kr-85m), and many others, the daughter resonant absorption nucleus being given in parenthesis.

For the Mossbauer radioisotope to experience stimulated emission of gamma rays it should be cooled below the temperature above which the Mossbauer effect is substantially suppressed, which temperature varies with the different radioisotopes, usually falling between 20° K. and 280° K. Thus for Co-57, Co-60 and Sn-119 the coolant temperature should be 20° K.-100° K., and for Tm-171 and Os-191, 70° K.-280° K. Cooling is required not only to prevent suppression of the Mossbauer effect but also to prevent the radioisotope self-heating to the point of structural destruction.

The Mossbauer radioisotopes usually in compound forms such as oxides or fluorides, formed into a long cylindrical rod and cooled below the temperature above which the Mossbauer effect is substantially suppressed, emit a superradiant beam of gamma rays out of both ends of the rod due to the progressive multiplication of gamma rays by the stimulated emission process (nuclear masing or "grasing") as the gamma rays travel in directions parallel to the axis of the rod. For off-axis directions the build-up of gamma rays by multiplication either does not occur or terminates when the gamma rays pass through the sides of the rod.

A more sophisticated emitter of coherent gamma rays according to the present invention deals with artificial control of the decay rate of the radioisotope by enhancement or decrease of nuclear emission in phase with an imposed signal. This adds time coherence to the emitted gamma rays, and by control of the beginning and the end and the intensity of the enhanced or decreased emission, modulation of the gamma ray emission. In general, a nuclear excited state will decay from a higher energy level to a lower level with the emission of a gamma ray but this decay is constrained by certain selection rules between the levels, as will be explained hereinafter. To enhance the de-excitation rate of radioisotopes artifically, several arrangements may be applied of which a preferred is to subject the radioisotope rod to an oscillating electromagnetic field with a frequency approximately equal to E_{2-3}/h where E_{2-3} is the energy difference between a metastable state and a nearby intermediate nuclear state of different spin, which plays the role of an activation energy for de-excitation, analogous to the activation energy in chemical reactions, and h is Planck's constant. The field at this frequency will cause the de-excitation rate from the long-lived metastable energy state through the intermediate state to a lower energy level to be enhanced. The spin directions of excited nuclei will "turn" or "flip-flop" out of phase with those of the electron clouds under the action of an oscillating electromagnetic field. At the proper frequency this effect will increase the probability that the metastable nucleus will change its spin to such a value that it can rapidly decay to a lower-lying energy state and therefore increase the

decay rate and enhance the emission of gamma rays above normal decay and emission. This change in spin is usually aided by an inner-shell electron which carries away some or all of the transition energy. This latter process is often referred to as an "internal conversion process," and it is usually this process whose rate is enhanced by the action of the oscillating electromagnetic field. When the frequency equals E_{2-3}/h approximately, this enhancement will be strongest and the frequency is called "resonant." Modulation of the intensity of the electromagnetic field will effect modulation of the emitted gamma ray beam.

For nuclides with very small values of E_{2-3}, the frequency given by E_{2-3}/h lies in the radio frequency region and therefore in one arrangement a radioisotope rod is placed inside a radio frequency coil such that it is coaxial therewith. Electric currents fed to the coil at a frequency approximately equal to E_{2-3}/h will then cause accelerated de-excitation of the radioisotope as described above.

Although a steady magnetic field is not necessary in order to achieve this frequency induced de-excitation, the presence of a strong transverse magnetic field will orient the nuclei and will cause the gamma rays to be emitted in preferred directions perpendicular to the direction of the field and thus along the axis of the rod.

The use of a coaxial radio frequency coil and a steady transverse magnetic field results in an apparatus which, coincidentally only, resembles a nuclear magnetic resonance instrument. However, the operational parameters used for coherent gamma ray generation are quite different from those used in nuclear magnetic resonance work and the underlying physical principles are quite different. In nuclear magnetic resonance work the main object is the determination of the value of the nuclear spin J of a nuclear isotope which may or may not be radioactive. The spin J is determined by studying the absorption spectrum of radio frequency power as a function of radio frequency f in the neighborhood of

$$f=\frac{g\mu_0 H}{h}$$

where g is the spectroscopic splitting factor of the nuclide and μ_0 is the nuclear magnetron. H is the magnetic field and h is Planck's constant. The frequency given by this equation for nuclear magnetic resonance work bears no relation to the frequency used for inducement of radioisotopic decay although, for certain materials, the frequencies may coincidentally have similar values. It will therefore be seen that while the structure used in an emitter according to this invention for the production and control of a superradiant beam of gamma rays may superficially resemble that used in nuclear magnetic resonance instruments, the operational frequency and the effect of nuclear masing and stimulated coherent gamma ray production is quite different.

Another modification of this invention lies in inducing nuclear decay in a cooled Mossbauer radioisotope rod by the application of ultrasonic frequencies thereto from an ultrasonic wave generator such as a piezoelectric crystal or a phonon maser which will vibrate at frequencies generally in the range of 1 to 10,000 gigacycles/sec. Modulation of the intensity of the ultrasound will effect modulation of the emitted coherent gamma ray beam. The ultrasonic application may be used with or without a nucleus-orienting transverse, steady, magnetic field. This ultrasonic application may be in place of or in addition to the use of the coaxial radio frequency coil. The ultrasonic frequency to be used should again equal E_{2-3}/h approximately, where E_{2-3} depends on the particular radioisotope that is used. In this arrangement, the radioisotope rod should preferably be of crystalline form with a lattice which will efficiently transmit sound at the frequency used.

In still other modifications of this invention, the Mossbauer radioisotope in a transparent crystalline form is formed into a long rod, cooled, and subjected to a beam of monochromatic light or laser photons or the rod is placed in or at the end of a microwave cavity. These modifications are desired when the frequency given by E_{2-3}/h falls in the microwave or optical range. The microwaves or optical photons should reach the nuclei in the solid rod without being excessively absorbed by atomic interactions and, hence, it is desirable that the solid state lattice of the rod material be transparent to the particular electromagnetic frequency being used. Modulation of the supplied electromagnetic energy will effect modulation of the emitted coherent gamma ray beam.

It is therefore a primary object of the present invention to provide an improved coherent gamma ray emitting device;

Another object of this invention is the provision of an improved gamma ray emitting device employing a long rod of excited radioisotope material in which there is stimulated emission of gamma rays from radioactive nuclei thus causing progressive multiplication of the gamma rays which travel parallel to the axis of the rod, analogously to the photons in a maser or laser;

Another object of this invention is the provision of an improved gamma ray emitting device employing an elongated rod of a Mossbauer radioisotope cooled below a temperature above which the Mossbauer effect is substantially suppressed and in which a substantially coherent beam of gamma rays is emitted from an end of the rod;

A further object of this invention is the provision of an improved device for controllably emitting coherent gamma rays comprising an elongated rod of a Mossbauer radioisotope cooled below the temperature at which the Mossbauer effect is substantially suppressed, in which emission is controlled by the application of a coaxial radio frequency field of a frequency to bring the internal conversion process into a resonant situation;

A still further object of this invention is the provision of an improved gamma ray emitting device in accordance with the preceding object in which the Mossbauer radioisotope rod is further subjected to a strong, transverse steady magnetic field;

Yet another object of this invention is the provision of an improved controllable coherent gamma ray emitting device employing an elongated rod of a Mossbauer radioisotope cooled below the temperature at which the Mossbauer effect is suppressed and in which the rod is subjected to controlled axial ultrasonic frequencies of a value to bring the internal conversion process into a resonant situation;

Still another object of this invention is the provision of an improved controllable coherent gamma ray emitting device employing an elongated rod of a Mossbauer radioisotope in a transparent crystalline matrix, the rod having an L/D ratio lying substantially between 5 and 40, in which the rod is cooled below the temperature at which the Mossbauer effect is substantially suppressed, the rod being subjected to a beam of electromagnetic energy of a frequency to bring the internal conversion process into a resonant situation.

These and other objects and features of the invention will be readily apparent to those skilled in the art from the following specification and the appended drawing in which:

FIGURE 1 is a diagrammatic representation of one form of a coherent gamma ray emitter device according to the present invention;

FIGURE 2 is a diagrammatic representation of another form of coherent gamma ray emitter according to the present invention;

FIGURE 3 is a representation of nuclear energy levels and spin states of excited nuclei in stimulated gamma ray emission according to the present invention;

FIGURE 4 is a diagrammatic representation of a coherent gamma ray emitter according to this invention

employing ultrasound to enhance the natural emission rate;

FIGURE 5 is an end elevational view of any of FIGURES 2, 4, 6 and 7;

FIGURE 6 is a diagrammatic representation of a coherent gamma ray emitter according to this invention employing a photon beam to enhance the natural emission rate; and

FIGURE 7 is a diagrammatic representation of a coherent gamma ray emitter according to this invention employing microwaves to enhance the natural emission rate.

FIGURE 1 illustrates a less complicated form of coherent gamma ray emitting device according to the present invention. An elongated rod 11 containing a Mossbauer radioisotope is mounted within a cavity 12 in a shield 13 of lead or other shielding material, the cavity being closed by a front plate 10 which also supports the front end of the rod. A coolant from a supply 15 is circulated through the cavity 12 to cool the rod 11. The coolant, which may be, for example, liquid nitrogen, maintains the temperature of the rod 11 below the value above which the Mossbauer effect is substantially suppressed. Gamma rays emitted from the end 16 of the rod 11 will be absorbed in the shield 13. Gamma rays emitted at 17 from the unshielded end 18 of the rod 11 will be in the form of a coherent beam which may be modulated by beam chopping means such as a perforated rotating wheel 19 placed in the path of the beam. This will be a superradiant, directionally coherent and partially phase coherent beam of gamma rays produced by progressive multiplication by stimulated emission from those gamma rays which travel parallel to the axis of the rod 11.

As has previously been described, the Mossbauer radioisotope emits gamma rays of monochromatic frequency so that they fall within the resonance width of the excited nuclei. With the isotope cooled below the temperature at which the Mossbauer effect is substantially suppressed, stimulated emission of excited nuclei thereby occurs within the rod and due to progressive multiplication of the gamma rays by the stimulated emission process along the axis of the rod, there is emitted from the end 18 a superradiant beam of gamma rays 17 which is directionally coherent and at least partially phase coherent.

As a specific example, the Mossbauer radioisotope can be Co–57 which decays with a 267 day half-life to Fe–57*m*. Fe–57*m* (isomer) has a half-life 10^{-7} seconds and decays to normal Fe–57 upon emission of a gamma of 15 kev. energy. As previously stated, the greater the *L/D* ratio of the rod 11 the more superradiant the gamma ray beam emitted. However, for practical considerations stimulated emission below an *L/D* ratio of 5 is not sufficiently significant to be important, and above 40 the construction of the rod becomes impractical and uneconomical. Preferably the *L/D* ratio of the rod from such practical and economic consideration lies between 10 and 20.

The basic structure so far described for FIGURE 1 may form in and of itself a complete coherent gamma ray beam emitter. It may be made more sophisticated by the provision of means for controlling the decay rate of the Mossbauer radioisotope of the rod 11 by the application of a radio frequency field thereto as shown in FIGURE 2, or the exposure of the rod 11 to ultrasonic waves as shown in FIGURE 4; exposure to a photon beam as shown in FIGURE 6; or exposure to microwaves as shown in FIGURE 7. For a consideration of artificial control of the decay rate of the radioisotope by the enhancement or decrease of nuclear emission over the natural decay rate, reference is made to FIGURE 3.

In general, a nuclear excited state will decay from a higher energy level to a lower level with the emission of a gamma ray but this decay is constrained by certain selection rules between the levels. One of these selection rules is that the order λ of the multipole radiation be such that $J_i+J_f \geqq \lambda \geqq (J_i-J_f)$, where the subscripts i and f stand for the initial and final state of the transition, and J stands for the nuclear spin. Another selection rule forbids the transition from a state with spin J=0, shown in FIGURE 3 as a metastable state 2, to another lower-lying state where J=0, such as state 1 in FIGURE 3. Even though energetically a direct transition from state 2 to state 1 is feasible, angular momentum conservation forbids it.

For an excited nucleus in the metastable state 2 to de-excite to the lower state 1, the nucleus must first go to an intermediate state with spin J=1, shown in the example of FIGURE 3 as state 3 which is close in energy to state 2. The extra energy and momentum required for the intermediate transition from state 2 to state 3 is, in naturally decaying radioisotopes, usually supplied by an inner core (K, L or M shell) electron of the atom of which the nucleus forms a part. This process whereby an inner orbit electron "helps" the excited nucleus to get over the "hurdle" which is represented by the angular momentum or energy difference J_{2-3} equals J_3-J_2 or $E_{2-3}=E_3-E_2$, is called "internal conversion" in nuclear physics and is well known in the art. Usually a particular orbital electron in the K, L or M shell which is denoted as e_c in FIGURE 3, possesses the most suitable relative energy, momentum and spin to assist the nucleus in going from state 2 to state 1 by way of state 3. In its natural state a radioisotope in state 2 will therefore de-excite by way of random internal conversion events. These de-excitations have half-lifes of for example 16 days for Os–191, 267 days for Co–57, and 1.9 years for Tm–171. To enhance the de-excitation rate of radioisotopes in state 2 artificially, it is desired to supply the nucleus-electron core system with a quantum of energy equal to the nuclear activation energy E_{2-3} of interaction between the nucleus and core electrons.

One way of providing this activation energy is to supply the electron-conducting coil 11 with radio frequency energy of a frequency approximately equal to E_{2-3}/h where h is Planck's constant and E_{2-3} is the energy difference between state 2 and state 3 in FIGURE 3. With the application of energy of this frequency the interaction between the nucleus and the conversion core electron can be brought into substantial resonance and the de-excitation rate from state 2 to state 1 by way of state 3 enhanced. The reason for this is that the radio frequency field will cause the radionuclide moments and the electron moments to oscillate and since there is a different lag between the nucleus and the core electrons in following the oscillations, changes in their relative angular-momentum-associated energies will result which will bring the internal conversion process into closer resonance.

If in a subsequent radionuclide de-excitation from state 1 to state 0 in FIGURE 3 a gamma ray is emitted, the effective emission rate of this gamma ray from the mother radioisotope is also enhanced. By pulsing or modulating the intensity of the impressed resonant electromagnetic energy, the emitted gammas are modulated and thus the emission is controllable and modulatable in time. Since the rod 11 is a gamma ray multiplying Mossbauer radioisotope there is also directional coherence in the emitted gamma ray beam 17 since the emitted gamma rays multiply along the axis of the rod 11 by stimulated emission.

The arrows 20 indicate that there is some stray gamma ray emission in all directions not cut off by shielding which does not form a part of the superradiant, coherent beam of gamma rays 17 which is emitted axially of the rod 11 and which has been built up by the progressive multiplication of gamma rays by the stimulated emission process of nuclear masing in the travel of gamma rays parallel to the axis of the rod.

FIGURE 2 shows a controllable coherent gamma ray emitter according to the present invention which, coincidentally only, takes the form of a nuclear magnetic resonance instrument. The elongated rod 11 contains a Mossbauer radioisotope, again cooled by a coolant circulating through the cavity 12 and is positioned inside a

conducting coil 14 which is supplied with radio frequency energy from a source 22.

The rear end of the rod 11 is shielded at 23 by lead or other material, and a strong magnetic field is applied transversely to the axis of the rod 11 by a magnet 24, which may be either a permanent magnet or an electromagnet, having poles at opposite sides of the rod; for example, a north pole 25 and a south pole 26, as illustrated in FIGURE 2. For very strong magnetic fields, it may be desirable to go to superconducting-coil electromagnet techniques to secure fields of the order of 100,000 gauss.

Although a steady magnetic field is not necessary to achieve radio frequency induced de-excitation, and thus controllable or modulation-coherent gamma ray emission, the presence of such a strong magnetic field orients the nuclei and causes the gamma rays to be polarized and to be emitted in preferred directions perpendicular to the direction of the field and thus along the axis of the rod 11. This results in a gain in directional or spatial coherence of the gamma ray emission. Modulation of the radio frequency energy will again effect like modulation of the emitted gamma ray beam.

The operational parameters used for coherent gamma ray generation according to the present invention are quite different from those used in nuclear magnetic resonance work, and the underlying physical principles are quite different. This is emphasized by the different factors involved in determining the different frequencies used in the coherent gamma ray emitter and in nuclear magnetic resonance instrument. While the optimum frequency for a coherent gamma ray emitter may be similar to the frequency used in some nuclear magnetic resonance work, this is only coincidental, as is shown by the different factors used to determine it.

Artificial control of the decay rate of the Mossbauer radioisotope in the rod 11 may be secured by application of ultrasonic frequencies thereto. This ultra sound may be used in place of, or in addition to, the radio frequency coil technique. In the use of ultra sound the rod 11 should preferably be made of crystalline form with a lattice which will efficiently transmit sound at the operating frequency which is again given by the energy equation $E_{2\text{-}3}/h$. Due to the different mass of the nucleus and electrons, the internal conversion process can again to brought into better resonance, resulting in induced gamma ray emission. By varying the intensity of the ultra sound, the emission can be time-controlled and modulated as before.

An emitter employing supersonic control of the decay rate is shown in FIGURES 4 and 5. A Mossbauer radioisotope rod 11 is provided with a cooling jacket 31 through which a coolant such as liquid nitrogen may be circulated. A transverse steady magnetic field may optionally be supplied by an electromagnet 32 having an energizing coil 33. A back shield of lead or other material is provided at 34 and a side shield at 30, the magnet also serving as shielding material. An ultrasonic wave generator and modulator is shown at 35. The wave generator may be a piezoelectric crystal, phonon maser, or other source of sound vibrations, having frequencies, by way of example, of the order of 10–1,000 gigacycles/sec. The rod 11 may by way of example be 1 millimeter in diameter and 20 millimeters long and made of Co–60 oxide. The ultra sound is applied axially to the back end 36 of the rod 11.

FIGURES 6 and 7 show other means for controlling or modulating the gamma ray emission according to this invention. In both the Mossbauer radioisotope rod 11 has the L/D relationship previously expressed and is cooled below the critical temperatures at which the Mossbauer effect in the radioisotope used is substantially suppressed. The cooling in both cases is effected by enclosing the rod in a jacket through which may be circulated a cryogenic fluid such as liquid nitrogen or the like in contact with rod 11. The electromagnet 32 may be omitted in each case, and where used functions the same as in FIGURES 2 and 4.

In FIGURE 6, the Mossbauer radioisotope rod 11 is subjected to a beam of laser photons or a monochromatic light beam. What photon frequency f is used will depend on the value of $E_{2\text{-}3}/h$. This frequency f will bring the internal conversion process into a resonant situation. The optical photons should reach the nuclei of the rod 11 without being excessively absorbed by atomic interactions and hence, the solid-state lattice of the rod material should be transparent to the particular photon frequency being used. FIGURE 6 illustrates a laser at 37 whose photon beam is modulated and directed at the back end of the rod 11 and through an annular window 38 in the back end of a transparent coolant-enclosing shell 39. The outer and front interior walls of the shell 39 are preferably aluminized or otherwise mirrored at 41 to reflect stray photons to the rod surface. A specific example for the FIGURE 6 configuration is a Tm–171 oxide or fluoride rod, 1 millimeter in diameter and 10–20 millimeters long. The laser can be a carbon dioxide-nitrogen pumped gas laser emitting 10.6 micron photons.

FIGURE 7 shows an emitter modification according to the present invention in which a cooled Mossbauer radioisotope rod is subjected to microwaves. A microwave generator and modulator at 42 transmits through a wave guide 43 to the back end of the rod 11. The microwave frequency is again determined from the energy state equation to bring the internal conversion process into a resonant condition. A typical example for the FIGURE 7 configuration is a rod of Cobalt 57 oxide, 1 millimeter in diameter and 10–20 millimeters long, using a microwave frequency of 80–150 gigacycles/sec. Modulation of the microwave generator output will effect modulation of the emitted gamma ray beam.

The coherent or superradiant beam of gamma rays emitted by the devices of this invention and indicated by the numeral 17 can be used in many applications, whether or not modulated. Where modulated, it is particularly useful in communications. Otherwise, it is useful in radiation weaponry, in the melting and evaporation of materials for the purpose of welding, cutting, machining, removal, plating, and other known uses for concentrated beams of energy, surgery, holographs, the ignition of nuclear fusion and others, and while certain preferred embodiments of the invention have been specifically illustrated and described herein, it is understood that the invention is not limited thereto, as many variations will be apparent to those skilled in the art, and the invention is to be given its broadest interpretation within the terms of the following claims.

I claim:

1. An emitter for coherent gamma rays comprising: a rod having a length to diameter ratio in excess of 5, said rod containing a radioactive isotope having substantially the characteristics of a Mossbauer radioisotope; and means for cooling said rod below the temperature above which the Mossbauer effect therein is substantially suppressed to secure stimulated emission of gamma rays within the rod and progressive multiplication of gamma rays along the axis of the rod to emit substantially superradiant, directionally coherent gamma rays from an end of said rod.

2. The gamma ray emitter defined in claim 1 in which said rod has a length to diameter ratio substantially between 10 and 20.

3. The gamma ray emitter defined in claim 1 including: means applying to said rod an oscillating magnetic field axially of said rod at a radio frequency to bring the interaction between an excited nucleus and a conversion electron into substantial resonance to enhance the de-excitation rate between energy state of the excited nucleus and to introduce at least radio frequency time coherence into the emitted gamma ray beam.

4. The gamma ray emitter defined in claim 3 including: means to apply a steady magnetic field substantially transversely of the axis of the rod to orient the nuclei of the radioisotope and cause the gamma rays to be emitted in preferred directions perpendicular to the direction of the field to secure a gain in directional coherence of the gamma ray emission along the axis of the rod.

5. The gamma ray emitter defined in claim 1 including: means for applying monochromatic ultrasonic waves to the end of said rod opposite the gamma ray emitting end to control the decay rate of the radioisotope, said rod being of a crystalline form whose lattice will efficiently transmit sound at the applied frequency.

6. The gamma ray emitter defined in claim 5 in which the frequency of the ultrasound is a function of the energy required to enhance the decay of the excited nucleus of the radioisotope from a metastable energy state to a lower energy state through an intermediate energy state by internal conversion with the help of a core electron.

7. The gamma ray emitter defined in claim 1 including: means for subjecting said rod to an electromagnetic beam of a wavelength to enhance the emission of gamma rays by bringing the internal conversion process of excited nuclei into a resonant condition.

8. The gamma ray emitter defined in claim 7 in which the wavelength of said electromagnetic beam is in the optical range and is generated by a monochromatic light source.

9. The gamma ray emitter defined in claim 7 in which said electromagnetic beam is in the microwave range and is transmitted to the end of said rod opposite the gamma ray emitting end by a wave guide.

10. The gamma ray emitter defined in claim 7 including: a modulator for said electromagnetic beam to effect modulation of the emitter gamma ray beam.

11. The gamma ray emitter defined in claim 7 including: means to apply a steady magnetic field substantially transversely of the axis of said rod to orient the nuclei of the radioisotope.

12. The gamma ray emitter defined in claim 3 including: a modulator for said radio frequency to effect modulation of the emitted gamma ray beam.

13. The gamma ray emitter defined in claim 5 including: means to apply a steady magnetic field substantially transversely of the axis of said rod to orient the nuclei of the radioisotope.

14. The gamma ray emitter defined in claim 5 including: means to modulate the intensity of the ultrasound to effect modulation of the emitted gamma ray beam.

15. The gamma ray emitter defined in claim 1 including: means to apply a steady magnetic field substantially transversely of the axis of the rod to orient the nuclei of the radioisotope and cause the gamma rays to be emitted in preferred directions perpendicular to the direction of the field to secure a gain in directional coherence of the gamma ray emission along the axis of the rod.

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ARCHIE R. BORCHELT, *Primary Examiner.*

U.S. Cl. X.R.

250—106

United States Patent

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[21] Appl. No. 705,417
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[45] Patented Jan. 19, 1971

[73] Assignees: Alexander Dawson, Inc., Mahwah, N.J., a corporation of Delaware, by mesne assignments:

[54] GAMMA RAY LASER HAVING A LOW TEMPERATURE CLOSED RESONATING CAVITY

6 Claims, 2 Drawing Figs.

[52] U.S. Cl. 250/84, 331/94.5

[51] Int. Cl. H01s 4/00,

[50] Field of Search 250/84, 331/94.5

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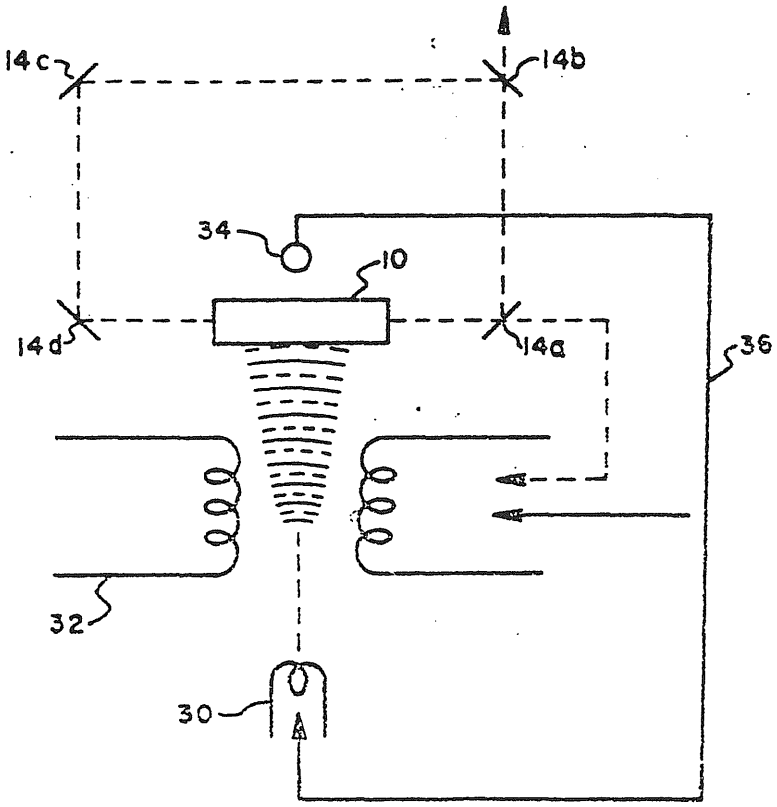
ABSTRACT: Gamma ray laser device, wherein a coherent beam of gamma radiation is generated through stimulation of gamma transitions in excited atomic nuclei in a biologically shielded and low temperature closed resonating cavity, and wherein said atomic nuclei are externally excited by subjection thereof to radiation produced by electron decomposition.



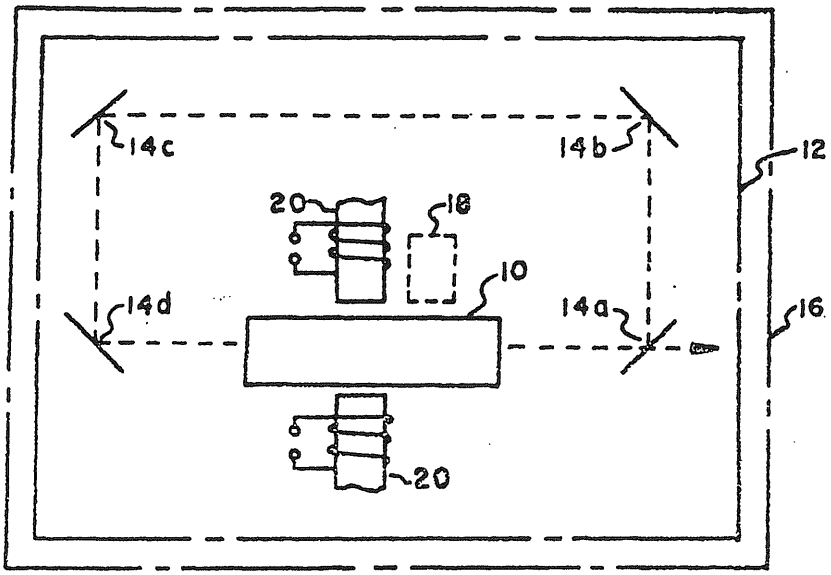


FIG. 1.

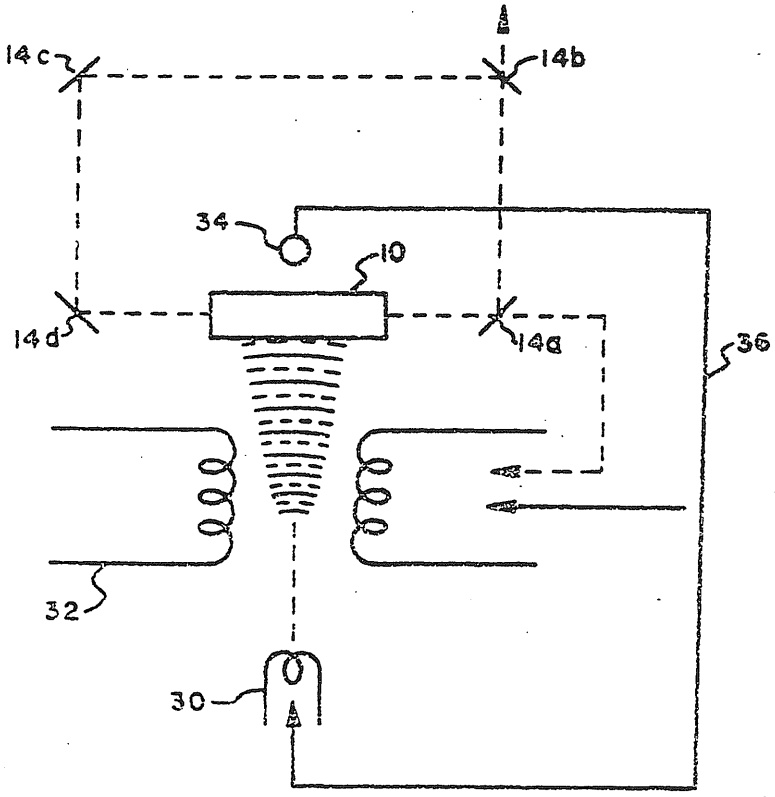


FIG. 2.

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GAMMA RAY LASER HAVING A LOW TEMPERATURE CLOSED RESONATING CAVITY

This invention relates to methods and devices for the production of coherent beams of ultrahigh frequency electromagnetic radiation and particularly to methods and devices for generating a coherent beam of gamma radiation of energy greater than 1 kilo electron volt.

To date, the field of operation of lasers and masers has been limited to the generation of light of wave lengths below the near ultraviolet range or of even longer wavelength light, heat and microwaves. In such devices, operability is dependent upon the stimulated emission of radiation from the electron shells surrounding the atom and such electron shell emission poses an inherent obstacle to the production of coherent ultrahigh frequency radiation of the type herein of concern.

This invention, in its broad aspects, employs the utilization of stimulated emission from the nucleus of the atom to effect the generation of a coherent beam of gamma rays which have wavelengths that are several orders of magnitude shorter than the wavelengths currently generated by conventional laser devices. Such gamma radiation inherently possesses an energy content that is several orders of magnitude greater than the energy content of radiation generated by conventional lasers. In its more narrow aspects, the subject invention includes method and apparatus for externally exciting atomic nuclei by radiation produced by electron decomposition to stimulate gamma transitions therein and to produce gamma radiation in a biologically shielded and low temperature closed resonating cavity through matching the emission process gamma transition energies to the absorption process gamma transition energies.

Among the advantages attendant the practice of the subject invention is the utilization of coherent gamma radiation in a focused beam for use either directly or as a trigger in varied fields which require or could utilize extremely rapid rates of release of tremendous quantities of energy, either in discrete bursts or at predetermined, periodically spaced intervals.

The principle object of this invention is the provision of a novel and improved method and apparatus for effecting the generation of coherent beams of gamma rays of energy of greater than 1 kilo electron volt by means of subjecting atomic nuclei to radiation produced by electron decomposition to stimulate gamma or transitions therein

Another object of this invention is the provision of a gamma ray laser device that may be utilized directly or as a trigger to effect the rapid release of tremendous quantities of energy in a predetermined manner. Other objects and advantages of the subject invention will become apparent from the following portions of this specification and from the appended drawings which illustrate, in accordance with the dictates of the patent statues, the essentials of presently preferred apparatus incorporating the principles of the invention and in which FIG. 1 is a schematic representation of essential components of apparatus for generating a coherent beam of gamma radiation of the general character described above.

FIG. 2 is a schematic representation of the utilization of a device of the type shown in FIG. 1 in association with apparatus for generating radiation by electron decomposition.

As schematically illustrated in FIG. 1, there is provided a source of gamma radiation 10, in which gamma transitions in excited atomic nuclei produce gamma radiation, a plurality of reflecting mirror members, such as the Bragg reflection mirrors 14*a* to 14*d* to define a closed circuit resonator cavity within which the emitted gamma rays are contained to reenter the source 10 and to thereby stimulate additional gamma transitions in excited atomic nuclei and means 20 for subjecting the atomic nuclei to selective magnetic and/or high frequency electromagnetic fields for matching the emission process gamma transition energies to the absorption process gamma transition energies. All of the above named components are enclosed within a cryostat, as generally designated by the dotted line 12, which in turn is surrounded by appropriate biological shielding means, generally designated by the dotted line 16. The following will serve to outline the theoretical basis for the operation involved and to define the parameters that affect the same.

In order to sustain oscillation in a laser, it is necessary that the following equation be satisfied:

$$e^{2(\alpha l-\beta l)} \geq \frac{1}{R} \tag{1}$$

where:

$\alpha = g_1/g_2 \sigma \Delta n$: is the gain/cm.
β = Loss/cm.: due to scattering, etc.
$g_1 g_2$ = Statistical weights of lower and upper levels
l = Length of the active medium
σ = Absorption cross section
$\Delta N = N_2 - \frac{g_1}{g_2} N_2$ is the inverted population
$N_1 N_2$ = Population of lower and upper levels.

In radioactive decay, we can represent the population of the upper level by

$$N_2 = R\lambda_2 e^{-\lambda_2 t} \tag{2}$$

where:

A = Initial activity in disintegration/sec.
τ_2 = Half life of the second level (3)
$\lambda_2 = 1/\tau_2$.

If we assume $\tau_2 \gg \tau_1$
then: $N_2 \gg N_1$, and

$$\Delta N \simeq N_2 = A\lambda_2 e^{-\lambda_2 t} = \frac{A}{\tau_2} e^{-t/\tau_2} \tag{4}$$

furthermore:

$$\sigma = g \frac{\lambda_0^2}{8\pi} \frac{T^2}{(h\nu_0 - h\nu)^2 + T^{2/4}} \tag{5}$$

where:

$T = \hbar\lambda(t)$
g = Statistical factor
$T = .693$
λ_0 = Wave length of relevant radiation
$\epsilon = h\nu_0 - h\nu$ = difference in energy of incident radiation and the energy of the excitation.

From equation 1 we obtain:

$$\alpha \geq \frac{1}{2l} \ln \frac{1}{R} + \beta \tag{6}$$

$$\sigma \geq \frac{g_2}{g_1} \frac{1}{\Delta n} \left\{ \frac{1}{2l} \ln \frac{1}{R} + \beta \right\} \tag{7}$$

with:

$a = 1.239 \times 10^{-4}$ cm.-ev.
$b = .693 \times 6.56 \times 10^{-16}$ ev.-sec.

we obtain:

$$\frac{g_n^2 b^2}{E_0^2 S \pi \tau_2^2 [\epsilon^2 + b^2 \tau_2^2]} \geq \frac{g_2}{g_1 \Delta n} \left\{ \frac{1}{2l} \ln \frac{1}{R} + \beta \right\} \tag{8}$$

with:

$$\Delta n = \frac{R}{\tau_2} e^{-t/\tau_2} \tag{9}$$

and:

$$c^2 = g \frac{g_1}{g_2} \frac{a^2 b^2}{8\pi}$$

results in:

$$\frac{c^2 A c^{-t/\tau_2}}{E_0^2 [T_2^2 \epsilon^2 + b^2 T]} \left\{ \frac{1}{2l} \ln \frac{1}{R} + \beta \right\} \geq 1 \tag{10}$$

The fraction of recoilless transition of gamma rays is approximately represented by:

$$f = \exp. \left\{ -\frac{3}{2} \frac{R}{k\theta_D} \left(\frac{4\phi(x)}{x} + 1 \right) \right\}$$

where:

$$x = \theta_D / t$$

and:

$$\phi(x) = \frac{1}{x} \int_0^x \frac{t d\xi}{e^{\xi} - 1}$$

θ_D = Debye temperature
Er = The recoil energy
T = The temperature in °K.

In order to maximize this expression, the Debye temperature should be as large as possible and the operating temperature should be small with respect to the Debye temperature.

The Zeeman effect produced by magnetic field gradients and/or the high frequency electromagnetic fields generated in the component 20 in effect produce emission and absorption energy line broadening which is used to minimize ϵ in equation 10, and hence to maximize the realizable gain. It can be observed from the final equation 10, that the following parameters are involved:

c is a constant;
A is the activity of the gamma ray source 10;
e is the base of the natural log system;
t is the time;
τ is the half life of the state in question;
E_0 is the transition of the state in question;
ϵ is the difference between emitted and absorbed gamma ray energy;
b is a constant;
l is the length of the active media;
R is the product of the reflectivities of the Bragg mirrors creating the resonant cavity;
β is the loss per centimeter.

It is readily seen that if the reflectivities of the Bragg mirrors are one, and the loss is zero, the total quantity on the left becomes large, thereby satisfying the equation. It can also be readily seen that if the half life τ is small, along with the energy difference ϵ, this will also help satisfy the equation. The equation also serves to define the basic requirements for source nuclei and thus permits selection of suitable materials that have attainable limits for E, l, R and β.

In the above described device, the gamma ray source 10 may suitably constitute a high purity crystal of radioactive material, or combination thereof, having a high curie temperature so as to provide a relatively high degree of recoilless emission of gamma rays. Additionally, the material utilized should be of such character that is not susceptible to electron and molecular interactions with applied magnetic fields to thereby minimize, if not avoid, all induced heating. The particular material employed must also have a metastable level appropriate to the particular mode of operation and to effect the emission of gamma radiation through transitions from the metastable state to a lower energy level. In order to effectively achieve the latter, the crystal should desirably be of highest obtainable purity so as to minimize, if not avoid, internal losses of appreciable magnitude that otherwise inherently occur due to the presence of substantial amounts of impurities within. Included among suitable radioactive materials useable as the gamma ray source 10 is Sn^{119m}, which possesses the necessary properties to satisfy the above requirements and which has a half life in the order of eight days. With such a material, the percentage of effectively recoilless emission of gamma rays during the transition from the metastable rate to a lower energy level is effectively increased by operating at low temperatures, for example, in the order of 10° Kelvin, within the cryostat 12.

In order to compensate for the energy differences which are normally attendant losses occurring during or subsequent to gamma ray emission, the emission process gamma transition energies are matched to the absorption process transition energies by subjecting the gamma ray source 10 to the action of a controlled magnetic field. This field may be of uniform character, or may be designed to provide a predetermined field gradient in accordance with the exigencies of a given installation. If a nonoscillating magnetic field is employed, internal energy level matching between emitting and absorbing nuclei in the active source material is effected by means of the Zeeman effect. Alternatively, such internal energy level matching can be effected by exposing the source 10 to electromagnetic field which functions to achieve effective line broadening and hence an increase in stimulated emission when the recoilless emission and absorption peaks are very narrow and close together Either or both types of energy level matching techniques may be utilized in any given installation.

In order to effect the necessary gain within the system, the emitted gamma radiation is reflected within a closed resonator cavity bidirectionally through the gamma ray source 10. Such desired reflection of the gamma radiation is effected by a plurality of Bragg reflection mirrors so arranged and positioned as to provide the requisite closed circuit defining the resonator cavity. Although four such mirrors are schematically illustrated, a greater number may be required and such will be determined by the frequency of the particular gamma radiation involved and the particular material of which the mirrors are made. The mirrors per se are constituted by crystals in which the crystal planes are free from internal defects and may be suitably constituted by pure germanium or silicon crystals. The mirrors are mounted in a so-called "puckered" arrangement as disclosed in "Resonator For An X-Ray Laser" by Bond, Duguay and Rentzepis, Applied Physics Letters, Vol. 10 No. 8, April 15, 1967. Each of the crystal mirrors must be mounted so as to permit the adjustment of the positioning thereof, and their initial positioning may be determined by x-ray diffraction techniques. Likewise focusing of the beam may be effected by physical warping of the mirror elements.

As will be apparent, one of the mirrors, for example the mirror 14*a*, must be so constructed so as to permit a portion of the coherent gamma ray beam to escape the resonant cavity and to exit from the device.

In a unit as above described, the gamma ray source 10 is of such character as not to require the application of any external excitation in order to effect the desired degree of transition from the metastable stable to the lower energy level. That is, the source material employed is possessed of a sufficient inverted population at the metastable state to provide, by stimulated emission, a sufficient gain to establish a coherent beam output.

As an alternative to the above, the subject device may include means 18 for externally exciting the source material to provide the necessary inverted population. One such means may comprise an auxiliary source of neutrons or other pumping mechanism to provide sufficient additional electromagnetic energy as to establish the necessary inverted population required to produce a stimulated gain as described above. With the use of such external excitation, a different selection and possible greater variety of gamma ray source materials are available for use. The characteristics of suitable source materials useable with external excitation include source materials of general character set forth above, together with materials of much shortened half life of the metastable state as determined by the amounts of pumping energy available. If a neutron source is employed for external excitation, such source, which suitably could comprise a nuclear reactor, should be adapted to provide the necessary quantities of thermal neutrons. When external excitation is employed the device will generally operate in a cyclic manner emitting bursts of energy at periodic intervals.

FIG. 2 schematically illustrates the association of a device of the type illustrated in FIG. 1 with apparatus adapted to supply radiant energy generated by the gamma ray source 10. As shown, there is provided means 30 for emitting a stream of high energy electrons, suitably an electron gun assembly. The stream of high energy electrons emitted from the source 30 is directed through an ultrahigh frequency oscillating magnetic field toward conductor target 34. The target conductor is connected by suitable energy transfer means 36 to both the electron source 30 and also to the generator means 32 for the magnetic field. In operation of the described device and with the frequency of the oscillating magnetic field set at a critical value between 10^{10} and 10^{14} cycles per second, the emitted electrons will be transmuted into positive and negative energy waves of discrete character as generally designated by the arcuate wave fronts 40. The negative energy waves are believed to be of conventional electromagnetic character and constitute gamma radiation of a particular character.

If, as illustrated, the gamma ray source 10 is disposed in the path of such radiation, the energy content thereof can be used in lieu of the neutron source to provide the requisite external excitation energy to create an inverted population of magnitude necessary to effect and maintain stimulated emission and high gain operation.

When so combined the gamma ray laser will in effect function as an energy conversion device wherein the gamma radiation source 10 absorbs the energy emanating from the electron decomposition device and converts it to coherent, monochromatic, collinear focused form.

As now will be apparent to those skilled in this art, the above described method and device may be utilized in a great number of diverse applications. In one aspect, the device may generally be thought of as an energy storage system capable of very rapid release rates. In other words, it can be viewed as a type of supercapacitor where the energy is released in the form of coherent gamma radiation. For instance, calculations indicate that when a one curie source of S_n^{119m} is stimulated, it will release its entire energy in a period of less than 100 nanoseconds, thereby providing an energy source of approximately 30,000 megawatts, which is at least 30 times the energy release obtained from large pulsed ruby lasers. Such high energy release rates could be employed for useful purposes such as for interception and destruction of missiles, tunneling through mountains, well drilling, and for road and canal building projects and the like. The coherent nature and wavelength of the emitted radiation also lends itself to numerous instrumentation oriented utilizations such as extremely accurate measurements of distance, time, velocity, and the like through adaption of interference techniques already in existence for optical lasers. In addition, and through means of holographic methods, magnifications on the order of 100 times that which may be achieved in electron microscopes are possible. Another major area of utilization for such a high intensity energy source would be the exciting of plasma and the triggering of other energy releasing nuclear reactions through controlled fusion or fission. In comparison with techniques presently being investigated for producing controlled fusion reactions, systems utilizing devices of the type herein disclosed would be relatively straightforward and less expensive to build.

We claim:

1. In the method of producing coherent gamma radiation the steps of stimulating gamma transitions in excited atomic nuclei to produce gamma radiation in a closed resonating cavity, matching the emission process gamma transition energies to the absorption process gamma transition energies, and externally exciting said atomic nuclei to create a population inversion at a metastable state by subjecting the same to radiation produced by electron decomposition.

2. The method as set forth in claim 1 wherein said atomic nuclei are subjected to electromagnetic radiation produced by electron decomposition.

3. The method as set forth in claim 1 wherein said atomic nuclei are subjected to positive energy radiation produced by electron decomposition.

4. Apparatus for producing coherent gamma radiation comprising:

crystal means adapted to produce gamma transitions in excited atomic nuclei;

means to match emission process gamma transition energies to absorption process gamma transition energies;

means for selectively directing emitted gamma radiation within a closed circuit resonating cavity for stimulating additional gamma transitions to effect emission of coherent gamma radiation; and

means for externally exciting said crystal means to create a population inversion as a metastable state by subjecting said crystal means to radiation produced by electron decomposition.

5. Apparatus as set forth in claim 4 wherein said crystal is subjected to electromagnetic radiation produced by electron decomposition.

6. Apparatus as set forth in claim 4 wherein said crystal is subjected to positive energy radiation produced by electron decomposition.

United States Patent [19]

Kaminskas

[11] **3,818,221**

[45] **June 18, 1974**

[54] **RADIATION GENERATOR PROVIDING AMPLITUDE MODULATION**

[75] Inventor: Rimvydas Kaminskas, Redondo Beach, Calif.

[73] Assignee: The United States of America as represented by the United States Atomic Energy Commission, Washington, D.C.

[22] Filed: Apr. 22, 1971

[21] Appl. No.: 136,344

Related U.S. Application Data

[62] Division of Ser. No. 868,704, Oct. 23, 1969.

[52] U.S. Cl. ..... 250/105, 250/106 S

[51] Int. Cl. G21f 3/00

[58] Field of Search ..... 250/106 S, 84, 84.5, 105

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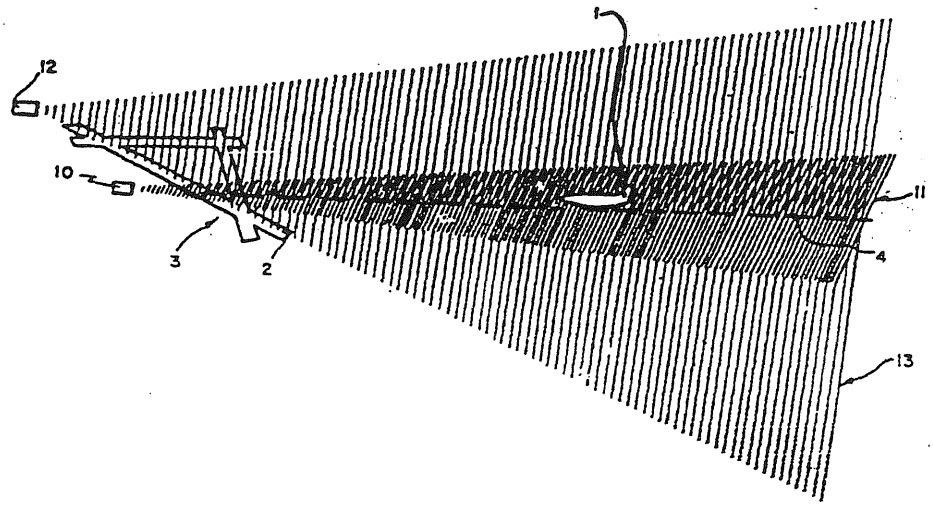
Primary Examiner—James W. Lawrence
Assistant Examiner—Davis L. Willis
Attorney, Agent, or Firm—John A. Horan

[57] ABSTRACT

An aircraft landing system based upon two or more beams of nuclear radiation is disclosed. Each beam is shaped by a radiation generator to conform to a desired pattern and is frequency modulated by the generator for identification and comparison purposes. Overlapping of two beams provides a spatial plane to serve as one reference such as a glide slope. A second pair of overlapping beams aligned substantially perpendicular to the first reference provides a second spatial plane to serve as a second reference such as a localizer beam. Appropriate circuitry aboard approaching aircraft is provided to determine the position of the aircraft with respect to the two reference beams.

9 Claims, 11 Drawing Figures



PATENTED JUN 18 1974

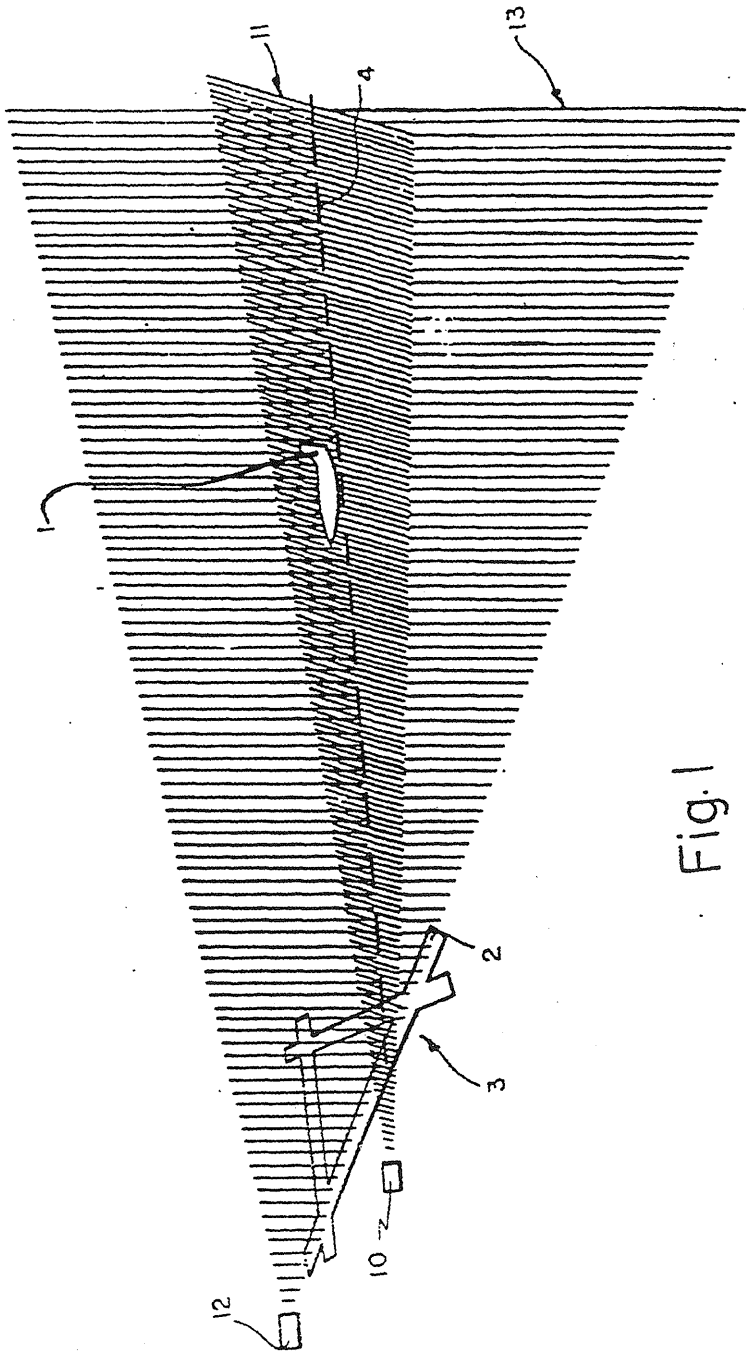


Fig. 1

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BY William B. Leach
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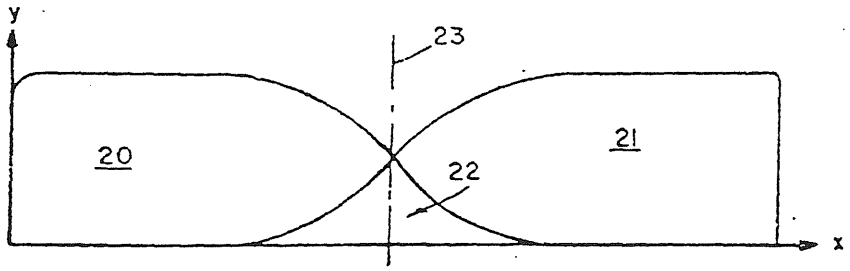

Fig. 3

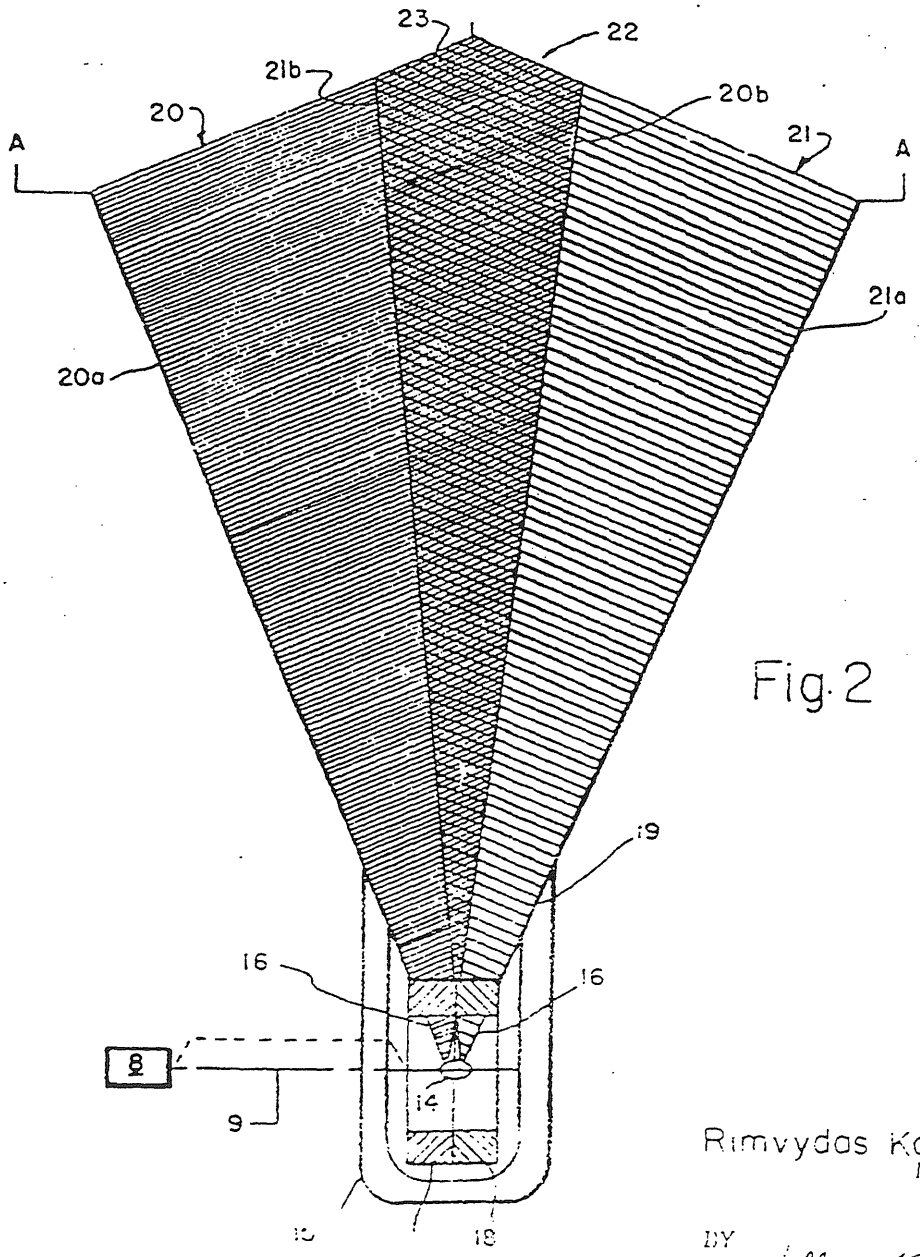

Fig. 2

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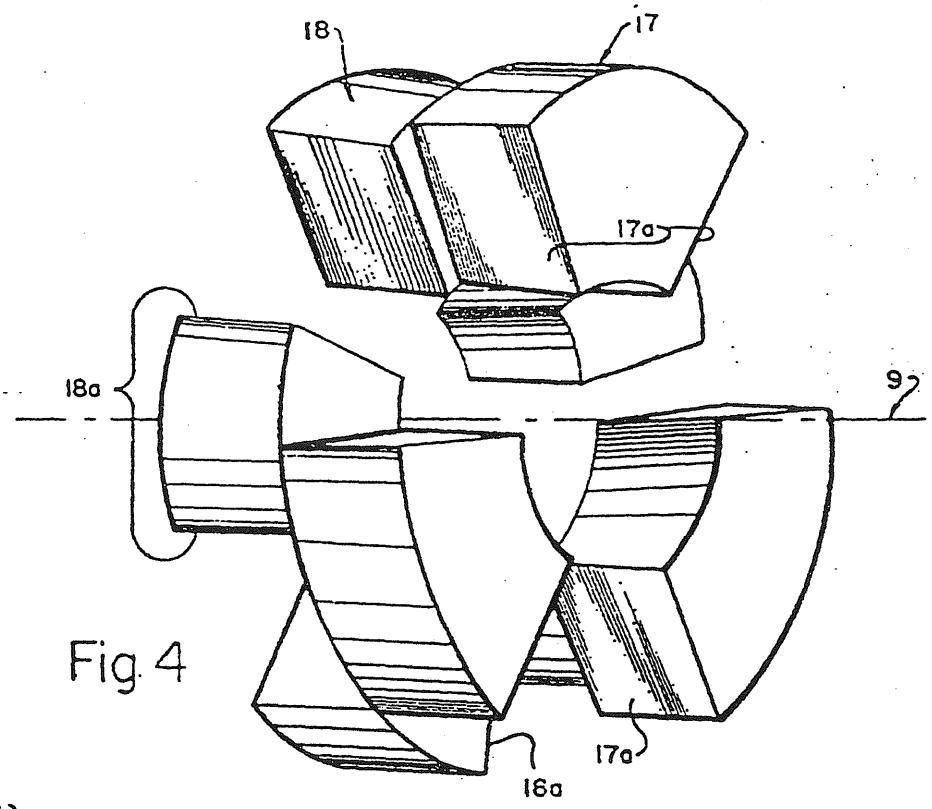

Fig. 4

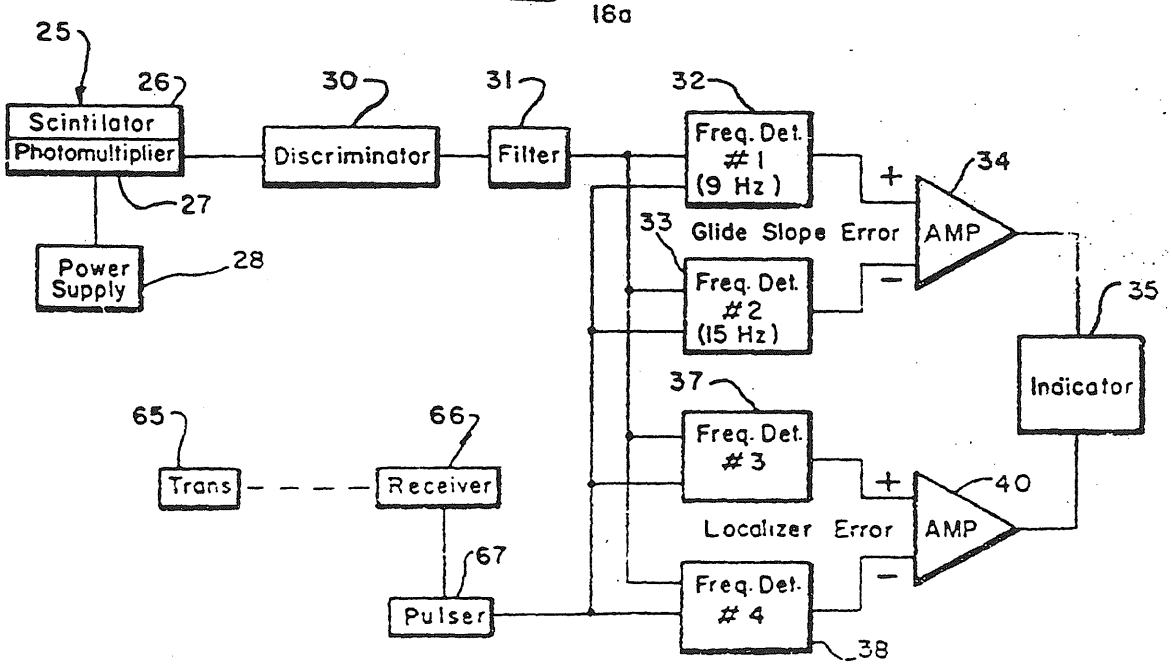

Fig. 5

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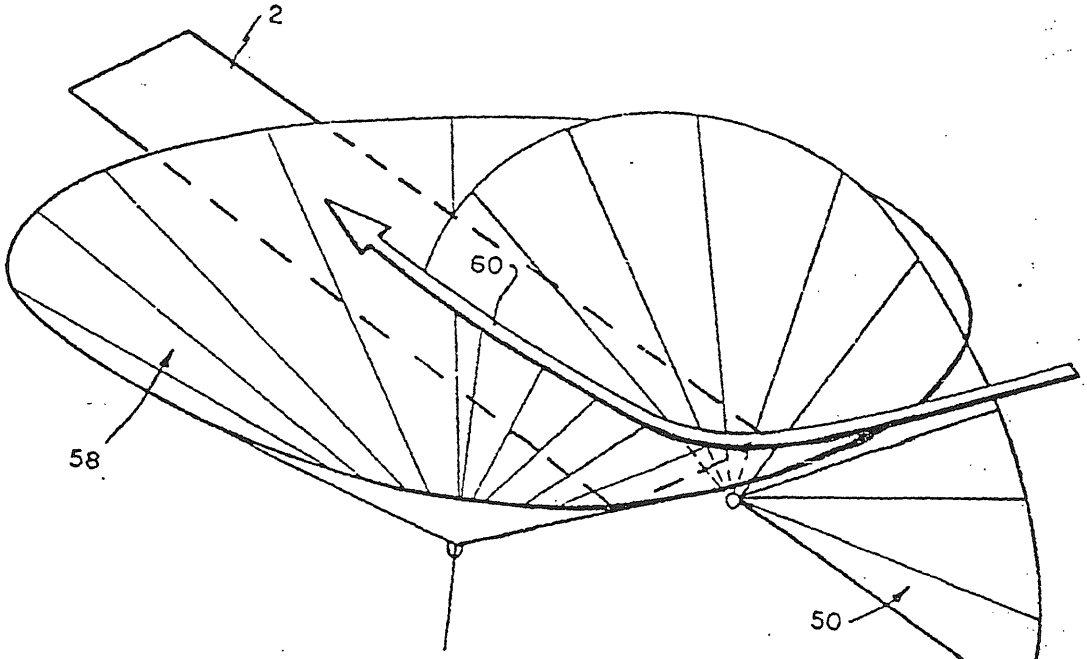

Fig. 6

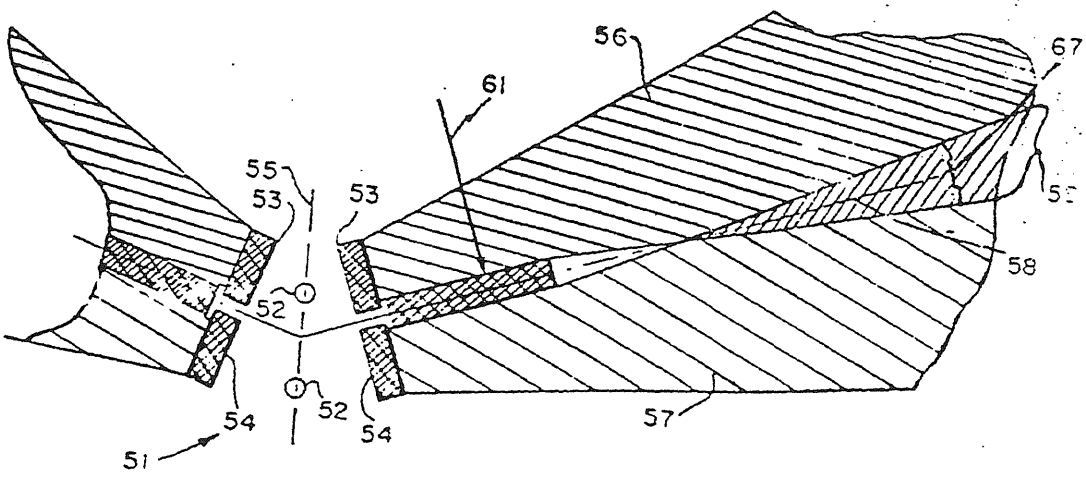

Fig. 7

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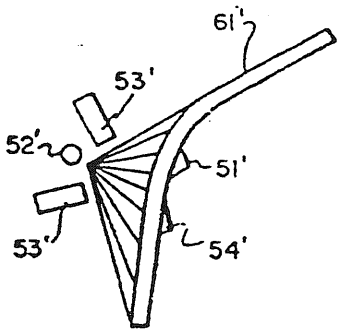

Fig. 8

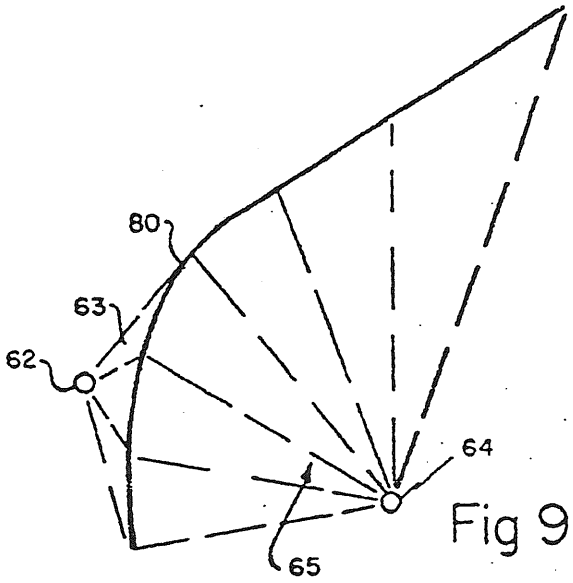

Fig 9

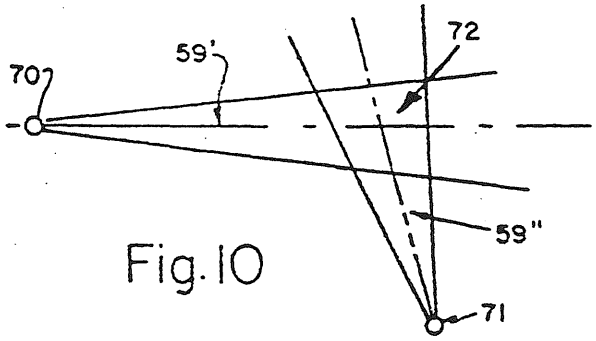

Fig. 10

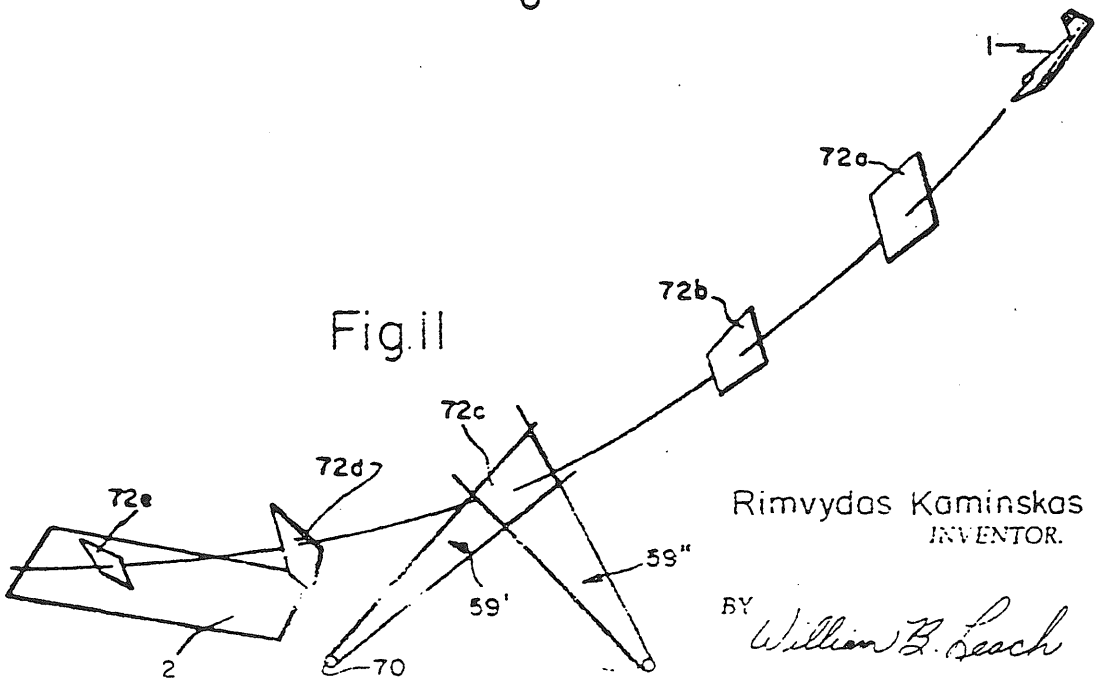

Fig. 11

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RADIATION GENERATOR PROVIDING AMPLITUDE MODULATION

BACKGROUND OF THE INVENTION

This is a division of application Ser. No. 868,704, filed Oct. 23, 1969.

Two aircraft landing systems widely used are known as the instrument landing systems (ILS) and the ground control approach (GCA). The conventional ILS systems contains two separate radio transmitters and arrays of transmitters antennas for the generation of localizer and glide slope radio beams. The localizer beam is a vertical fan of radiation which is used to guide an airplane in the horizontal plane to intercept the end of the runway. The glide slope makes up a horizontal plane of radiation which intersects the ground at the touch down point near the end of the runway and slopes at approximately 2.5° to provide guidance to approaching aircraft in the vertical direction. The intersection of the localizer and the glide slope plane forms a line in space which leads the approaching airplane to the end of the runway. Marker beacons, which are low power vertical fans of radiation, may be used to indicate to the pilot his progress along the approach path. These markers are identified as the outer, middle, and inner marker by different frequencies of modulation. The inner marker is usually located about 250 feet from the runway.

The localizer and glide slope beams each consist of two lobes of radio frequency radiation. One lobe is modulated at 150 HZ and the other modulated at 90 HZ. The intersection of the two lobes forms a plane which, when positioned horizontally, is used as the glide slope, and when positioned vertically is used as the localizer.

The localizer and glide slop signals are received in the aircraft by means of several antennas and receivers. Each receiver output actuates a common instrument having two indicator needles which indicate to the pilot his position with respect to the two reference beams. The aircraft is directly on the approach course when the two needles cross in the center of the instrument indicating that equal amounts of 90 and 150 cycle signals are being received from the localizer and glide slope receivers.

The presently used landing systems do an excellant job of guiding an airplane from a distance of many miles to the inner marker. However, from the inner marker, a few hundred feet from the end of the runway, the pilot is on his own and has to make the landing visually. The necessity of making a visual landing during the last few hundred feet is required because the radio beams of the instrument landing system interfere and reflect from the ground and other objects around the runway. This interference will, of course, cause a deterioration in the accuracy of the system just at the time when most precision is required. Also, the presently used landing systems provide a convergent beam that converges to a point at the origin near the landing point thus varying the size of the corridor that the aircraft has to fly in as a fraction of distance from the origin of the beams.

It is accordingly an object of the present invention to provide a radiation generator or beacon for an instrument landing system which is not subject to these and other disadvantages and limitations of the prior art.

It is another object of the present invention to provide a radiation beacon for an instrument landing system which is not significantly affected by weather conditions.

A further object of the present invention is to provide a radiation beacon for an instrument landing system which is highly reliable and reasonable in cost.

It is another object of the present invention to provide a radiation beacon for providing a curved reference path for determining the position of an object relative thereto.

SUMMARY OF THE INVENTION

The present invention provides apparatus for generating one or more patterns of radiation which are intensity modulated for determining the position of an object such as the position of an aircraft with respect to a landing area. The apparatus permits the step of generating a first and second three dimensional pattern of radiation. The patterns are directed so as to overlap and are modulated at predetermined frequencies. The overlapping regions are of changing intensity, thus a spatial plane may be defined which includes equal amounts of radiation from each pattern. A radiation sensing device, in association with the object to be located, may be used to sense the position of the object within the radiation patterns.

Similar apparatus may be used for the generation of a second spatial plane which intersects the first spatial plane. The intersecting spatial planes of radiation define a line in space thereby providing a reference from which to determine the position of an object. The intersecting radiation planes may be shaped by the beacon, for example, generating shapes including hyperbolic, or other arbitrary patterns which provide a line in space or a selected curvature to aid maneauvers such as a flare prior to intersecting with the runway.

The beacon includes a radiation shield in which is provided an aperture. A radiation source is placed within the shield and modulating means permit radiation to emit through the aperture at a predetermined frequency. The shutter and shield may be designed to emit two overlapping radiation patterns and which may be formed to have decreasing intensities within the overlapping regions.

Further, means are provided for defining a flight corridor which has a substantially constant cross-section. This is accomplished in part by the use of a selectively shaped radiation absorber which serves to alter the radiation patterns.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagrammatic representation of an example of a position sensing system constructed in accordance with the principles of the present invention;

FIG. 2 is a diagrammatic representation of a radiation beacon in accordance with the principles of the present invention that may be used in the position sensing system of FIG. 1;

FIG. 3 is a graph of the transverse radiation distribution in the radiation pattern of FIG. 2;

FIG. 4 is a perspective view of a shutter device used in the radiation beacon of FIG. 2;

FIG. 5 is a schematic diagram of a receiver for radiation sensing and position indicating suitable for use in association with the object whose position is to be determined;

FIG. 6 is a diagrammatic representation of another example of the position sensing system constructed in accordance with the principles of the present invention wherein a curved flight path is defined;

FIG. 7 is a diagram of a beacon shutter device used in forming the conical beam of FIG. 6 and further including a radiation absorber for shaping the radiation patterns;

FIG. 8 is a diagrammatic representation of the radiation beacon of FIG. 7 adapted to generate a particular flight path;

FIG. 9 is a representation of a flight path generated in part by the beacon of FIG. 8;

FIG. 10 is a representation of two radiation beams used to define a constant cross-section flight corridor; and

FIG. 11 depicts a constant cross-section flight corridor formed as in FIG. 10.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIG. 1, there is depicted an aircraft 1 approaching one runway 2 of airport 3. A first radiation beam or glide slope beacon 10 forms a pattern of radiation which defines a glide slope reference-plane 11. A second radiation beam or localizer beacon 12 forms another pattern of radiation which defines a localizer reference-plane 13. The intersection of the reference planes 11, 13 form a line 4 in space along which the aircraft 1 may be flown to landing. As does an aircraft using a conventional ILS system, the aircraft 1 senses and determines its position with respect to each reference plane of radiation.

In accordance with the principles of the present invention, the reference beams consist of radiation having short wavelengths. A short wavelength herein refers to radiation having a wavelength equal to or shorter than that of visible light. Gamma radiation is particularly suited to the practice of the invention, however, visible light, such as from a laser system, may be used.

The reference plane 11, 13 of FIG. 1 may be produced with the aid of the device shown in FIGS. 2 – 4. A radioisotope source 14 in a housing 15 emits gamma rays 16 which are intermittently passed through a pair of shutters 17, 18. The housing 15 completely encloses the radioactive source 14 and shutters 17, 18 except for an aperture 19 therein. The housing 15 may be of concrete or metal construction and serves to collimate the gamma radiation in a desired direction and to otherwise eliminate radiation in undesired direction.

The shutters 17, 18 are rotated about an axis of revolution 9 by a motor 8. As shown in FIG. 4, the shutters are essentially ring-shaped members or a cylindrical member having radial openings therein 17*a*, 18*a*. The shutter 17 is provided with three such radial openings and the shutter 18 is provided with five such radial openings. By way of example, if the shutters 17, 18 are revolved at 3 revolutions per second, the radiation frequency emitted through the one shutter 17 would be $9H_z$ and in the case of the other shutter 18 the radiation frequency would be $15H_z$. The shutter portions 17, 18 may be constructed as an integral unit or as separate units each driven at a particular speed of revolution. Furthermore, the number of radial openings may be varied to provide any desired frequency. Thus, as shown in FIG. 2, the radiation passed through the shutter 17 forms a first pattern of radiation 20 having a first predetermined frequency. The radiation passed through the other shutter forms a second pattern of radiation 21 and has a second predetermined frequency. The two frequencies of radiation are indicated in the drawings by differing the spacing of the lines representative of the radiation patterns.

The shutters 17, 18 and radioisotope source 14 are designed and arranged to direct the two patterns of radiation 20, 21 into a sensitive or an overlapping area 22. The intensity of the radiation is varied transversely within each of the radiation patterns 20, 21. This variance in intensity is depicted graphically in FIG. 3 wherein the Y axis represents radiation intensity and the X axis indicates transverse distance in the radiation pattern taken along section line AA of FIG. 2.

From FIGS. 2 and 3 it may be noted that the first radiation pattern 20 has a greater intensity in the region of its one edge 20*a* and decreases to a minimum in the region of its other edge 20*b*. Similarly, the intensity of the radiation in pattern 21 is maximum near its one edge 21*a* and minimum near its other edge 21*b*. The overlapping of the two radiation patterns 20, 21 into sensitive area 22 defines a centerplane or zone 23 wherein there is equal amounts of radiation from each pattern.

This center-plane 23 may become a reference plane for sensing the position of an object with respect thereto. If the center-plane 23 of FIGS. 2 and 3 is oriented vertically, it may become the localizer beam 13 of FIG. 1. Similarly, the center-plane 23 may become the glide-slope beam of FIG. 1.

It will be appreciated that to form a center-plane, two patterns of overlapping radiation must be generated and for detection purposes that each pattern of radiation must have a characteristic frequency. It may be noted that the relative amplitude of the two radiation patterns will be approximately the same at any radial position from the source of radiation. A radiation detection system which measures the relative amplitude of the two overlapping radiation patterns and which is located in the center-plane of the two radiation patterns will detect and measure equal amplitudes of radiation of each frequency. If the detector is moved away from the center-plane, greater amplitude of one frequency and less amplitude of the other frequency will be detected. Upon further movement of the detector away from the center-plane, the amplitude of one frequency of radiation will become zero. The detection system need only measure the relative amplitude rather than absolute values of intensity. The foregoing information may be utilized to indicate the relative position of the detector or receiver with respect to the center-plane. In the case of aircraft, it has been noted that two such center-planes would be formed. In this case there will be four characteristic frequencies involved, two for each center-plane.

The accuracy of the nuclear instrument landing system disclosed herein is determined by the accuracy associated with the definition of nuclear beam and the accuracy of the nuclear beam detection. As to the definition of the nuclear radiation beams or center-plane, this is a function of the geometry used in the source-shutter assembly design. Using a cobalt-60 radiation source and an 8 inch diameter shutter will provide a definition in the order of ± 1 foot at the range of 200 feet. The accuracy of the nuclear beam detection is pri-

marily a function of the count rate received by the detector which determines the signal to noise ratio between the individual frequencies used for formation of the radiation beams. The accuracy, therefore, will tend to increase sharply as the aircraft approaches closer to the source because the count rate will increase, and also because the definition of the individual frequencies will become better. Thus, the system inherently provides the highest accuracy near touch down just when the highest accuracy is needed.

The radiation from the radioactive source is not a hazard to the personnel. By way of example, the glide slop beam and localizer beam may be generated by two radioisotope sources of 10 curies each of cobalt-60. If an approaching aircraft is at an average distance of 200 feet away from the radioactive source and if the aircraft spends an average of one minute making the final decent and landing, the radiation dose received by the personnel in the airplane will be in the order of magnitude less than 0.25 milliroentgen per landing. The radiation beam may be shielded so as not to expose personnel in the terminal area to unnecessary radiation. A shield constructed of lead 10 inches thick will reduce the radiation from the 10 curie cobalt-60 source to a level equivalent to 0.1 millicuries of cobalt-60.

The modulated radiation patterns as heretofore described may be suitably detected and the position of a radiation detector determined with respect to the center-plane of any two radiation patterns. A suitable detection circuit is shown in FIG. 5. A detector 25 senses the presence of radiation of the type emitted by the radiation generator. The detector 25 may consist of a scintilator 26, a photomultiplier tube 27. A high voltage power supply 28 is provided to power the photomultiplier tube. If the detector 25 is placed within the radiation patterns of FIG. 2, the detector 25 may sense either of two characteristic frequencies of radiation or a combination thereof. If the detector 25 senses a combination of the two radiation patterns and the relative amplitudes thereof are the same, the detector 25 is then located in the center-plane 23. As has been explained, the radiation center-plane 23 of FIG. 2 may serve as either the glide slope beam or localizer beam of a landing system. A similarly generated center-plane of radiation may be generated to form the other of the guidance beams in a landing system. In such a case, the detector 25 of FIG. 4 may sense any one of four modulated radiation patterns or any combination thereof.

In further reference to FIG. 5, the electrical output signal from the detector 25 is impressed upon various signal processing circuits including a discriminator circuit 30 which serves to distinguish the signal radiation from background noise. The output of discriminator 30 is impressed upon a filter circuit 31 wherein undesired frequencies are attenuated. The filter output is then impressed upon at least a pair of frequency detection circuits 32, 33 each of which is designed to recognize a signal frequency associated with one of the radiation patterns. As heretofore indicated, typical frequencies might be 9 and 15H. The pair of frequency detectors 32, 33 are each designed to provide a direct current output representative of the detected frequencies. These outputs are then summed by an operational amplifier 34 the output of which is impressed upon an indicator 35. The indicator 35 may be in the form of a galvanometer or other instrument which conveys information to an operator. The indicator 35 is calibrated to indicate the relative amplitudes of the two signals provided by the frequency detection circuits 32, 33 which in turn are representative of the relative amplitude of the modulated radiation patterns sensed by detector 25. For example, if the detector 25 is placed in the radiation pattern of FIG. 2, the relative amplitude of the radiation patterns 20, 21 depends upon the position of detector 26 with respect to the center plane 23. If center-plane 23 of FIG. 2 is representative of the glide slope of FIG. 1, then the indicator 35 of FIG. 5 will provide a reading representative of that position.

As previously described, the center-plane 23 of FIG. 2 may be appropriately orientated to serve as the localizer beam 13 of FIG. 1. The circuit of FIG. 5 may be appropriately modified to sense the two additional radiation patterns associated with the localizer beam each of which is modulated at a characteristic frequency. The modification of the circuit in FIG. 5 would include the addition of a second pair of frequency detection circuits 37, 38 the outputs of which are impressed upon a second operational amplifier 40. The operational amplifier 40 adds the signal outputs of the frequency detection circuits 37, 38 to provide an output signal which is representative of the position of detector 25 with respect to the localizer beam. This amplifier output signal is impressed upon indicator 35 wherein the information is conveyed to an operator in a convenient form. The operational amplifier outputs may be simply used to form audial tones the amplitudes of which are compared by an operator.

The detection sensitivity and the range of the landing system may be enhanced by adding phase-lock features to the system. The shutters 17, 18 of FIG. 4 may be designed and arranged to simultaneously interrupt both of the radiation patterns 20, 21 of FIG. 2 thereby defining a portion in each cycle of revolution of the shutters during which no radiation is emitted. During this blank portion of the cycle, a signal representative thereof may be used to excite the detection circuit thereby coordinating the phase of the modulated radiation patterns and the frequency detection circuits of FIG. 5. Thus, in FIG. 5, a reference signal transmitter 65 provides a reference signal to a reference signal receiver 66 which impresses the reference signal upon a pulser circuit 67. The latter has an output signal which is impressed upon each of the frequency detector circuits 32, 33, 37, 38 for the purpose of initiating a low amplitude excitation reference pulse therein. In this manner, the frequency detection circuits each oscillate at their tuned frequency, i.e., at the frequency to be detected and are in phase with the signal representative of the radiation. Thus, a very weak radiation signal will be detectable since the signal to be detected will be added to the reference pulse.

Other embodiments of the invention described herein may be used to provide flight paths which are curved such as might be desirable for flare before touchdown or flight paths for short takeoff and landing aircraft. Such an embodiment is shown in FIGS. 6 and 7 wherein a localizer beam 60 is formed by a vertical center-plane of radiation modulated at two frequencies just as was the localizer beam heretofore described. The glide slope beam however is formed in the shape of a cone by making a conical shutter assembly or beacon illustrated in FIG. 7 which serves the same purpose as did the shutter assembly of FIG. 4.

The apparatus includes a double shutter assembly similar to that of FIG. 2. As diagrammed in FIG. 7, each of a pair of shutters is a substantially torroidal element which revolves about an axis of rotation 55 and has a number of slots through which radiation may pass. The assembly includes a housing with an opening therein whereby the torroidal element may be rotated to periodically register the slots with the opening in the housing thereby defining a shutter system. An upper shutter is simply depicted at 53 and a lower shutter at 54.

As heretofore explained, one or more radiation sources 52 emit radiation which when periodically interrupted by the shutters define a first and second radiation pattern 56, 57 which intersect to form a sensitive zone 59 in which a center-plane 58 of equal intensity radiation exists.

Other variations in the shape of the radiation beams or patterns may be provided by the use of a radiation absorber, such as a lead shield, placed radially from the radiation source and between the intersecting patterns of radiation. Such an arrangement is shown in FIGS. 7 and 8 which may be used to provide the aircraft approach path shown in FIG. 9.

Referring to FIG. 7, an absorber 61 is positioned as shown and serves to selectively modify the overlapping characteristics of the radiation patterns 56, 57. The beacon apparatus of FIG. 7 is shown in FIG. 8 in conjunction with a selectively shaped radiation absorber 61'. The radiation from source 52' is periodically emitted through a shutter assembly, depicted at 53' to form a modulated pattern of radiation on one side of absorber 61'. Radiation emitted through the other shutters depicted at 54', forms the second modulated radiation pattern which intersects the first pattern to define an overlapping sensitive area as heretofore described. Within the sensitive area is the center-plane or zone of equal intensity radiation which may be used as a reference for determining position of an object with respect thereto.

The beacon apparatus of FIG. 8 is represented in FIG. 9 by the numeral 62 and is shown as generating a curved reference zone or center-plane 63 which conforms substantially to the shape of the absorber 61' of FIG. 8. A second beacon 64, similar to the apparatus of FIG. 8, forms another reference zone of radiation 65 which intersects the curved reference zone of radiation 63 thereby defining a curved line 66 in space which may serve as a flight path for aircraft. Such a curved flight path is particularly suited to helicopter and STOL type aircraft.

The use of an absorber material to selectively shape the radiation patterns is particularly suited to the guidance of high speed aircraft. The apparatus used to generate a glide slope is typically installed along side of the landing strip. If the apparatus of FIG. 2 is used to generate a glide slope, the axis of radiation of the shutters would be oriented vertically which means that the portion of the glide slope near the landing strip would be created by angularly sweeping radiation patterns. It is feasible that the landing speed of an aircraft might approach the sweep of the radiation patterns os as to place the aircraft in a zone which is continuously absent of radiation or at least to create a situation in which a doppler effect would make signal recognition impractical, thus, the aircraft would have no position determining capability. This condition may be avoided by substantially aligning the axis of rotation of the shutters with the flight path of the aircraft.

The invention described herein may be used in yet another manner which provides a substantially constant size flight path corridor. The state of the art ILS and the landing system described herein in conjunction with FIG. 2 provide a sensitive area 22 which becomes narrower as the aircraft approaches touchdown, thus, it becomes increasingly difficult for the pilot to maintain the aircraft within the sensitive area or flight corridor.

A constant size corridor may be generated in accordance with the principles of the invention herein. Reference is made to FIG. 7 wherein it may be noted that the included angle within the sensitive area 59 may be varied by changing the radial dimension of radiation absorber 61. Thus, if a particular length is selected for a cord of a circle which traverses the sensitive area 59, the radial location of the cord of the selected length will vary as a function of the absorber size. For example, the cord dimension 67 will be located nearer the radiation source 52 if the absorber 61 is removed because the included angle of the sensitive area 59 will be larger.

These observations are used in FIG. 10 wherein one radiation beacon 70 generates a first sensitive area 59' and another radiation beacon 71 generates a second sensitive area 59''. The intersection of the two sensitive areas 59', 59'' define a flight corridor 72 having dimensions which are a function of the included angle of the sensitive areas and the radial distance from the sources. These factors may be controlled by proper selection of the radiation absorber configuration. This technique is shown in FIG. 11 wherein the beacons 70, 71 generate intersecting sensitive areas 59', 59'' to define a corridor depicted in two dimensional segments 72*a* – 72*e*. An aircraft 1 ascertains its position with respect to the corridor as heretofore described.

If the radiation intensity is varied transversely throughout the patterns, as was the case with the radiation patterns with FIG. 2, a conical center-plane 58 will be formed which may be used as a reference for determining the position of a radiation detector with respect thereto.

The conical radiation center-plane 58 of FIG. 7 is also shown in FIG. 6 wherein it serves as a glide slope beam and is directed and positioned so as to intersect the vertically orientated localizer beam 50. The intersection of the two beams 50, 58 form a parabolic line in space 60 which may serve as the flight path to be followed by an approaching aircraft.

What is claimed is:

1. A radiation generator for housing a source of radiation therein and for forming a pattern of radiation, comprising:

a. shielding means for permitting the escape of radiation in preselected directions;

b. first shutter means operably associated with said shielding means for periodically interrupting a portion of the escaping radiation at a first preselected frequency; and

c. second shutter means operably associated with said shielding means for periodically interrupting another portion of the escaping radiation at a second preselected frequency, said shielding means being dimensioned to direct said one and said other

portions of radiation into an overlapping relationship.

2. The radiation generator of claim 1 wherein each said shutter means comprises a substantially clyindrical member designed to have a source of radiation positioned therein and having open radial sections through which radiation may escape, said cylinder member being positioned to permit each open radial sector to periodically register with the escaping radiation when said cylinder is revolved.

3. The radiation generation of claim 2 wherein said generator is orientated to vertically align the axis of said cylindrical member whereby the angular sweep of the emitted radiation pattern will be horizontal.

4. The radiation generator of claim 2 further comprising means for rotating said cylindrical member at a predetermined angular speed thereby providing a predetermined frequency of radiation emission.

5. The radiation generation of claim 1 further comprising a radiation absorber positioned external said shutter means and so located as to interrupt a portion of emitted radiation, said radiation absorber being selectively shaped so as to impart a preselected configuration of radiation.

6. A radiation generator comprising:

a. a source of short wavelength radiation;

b. shielding means associated with said radiation source for permitting the escape of radiation in preselected directions;

c. shutter means operably connected to said shielding means for periodically interrupting one portion of the escaping radiation at one characteristic frequency to define a first radiation pattern and for interrupting another portion of the escaping radiation at another characteristic frequency to define a second radiation pattern.

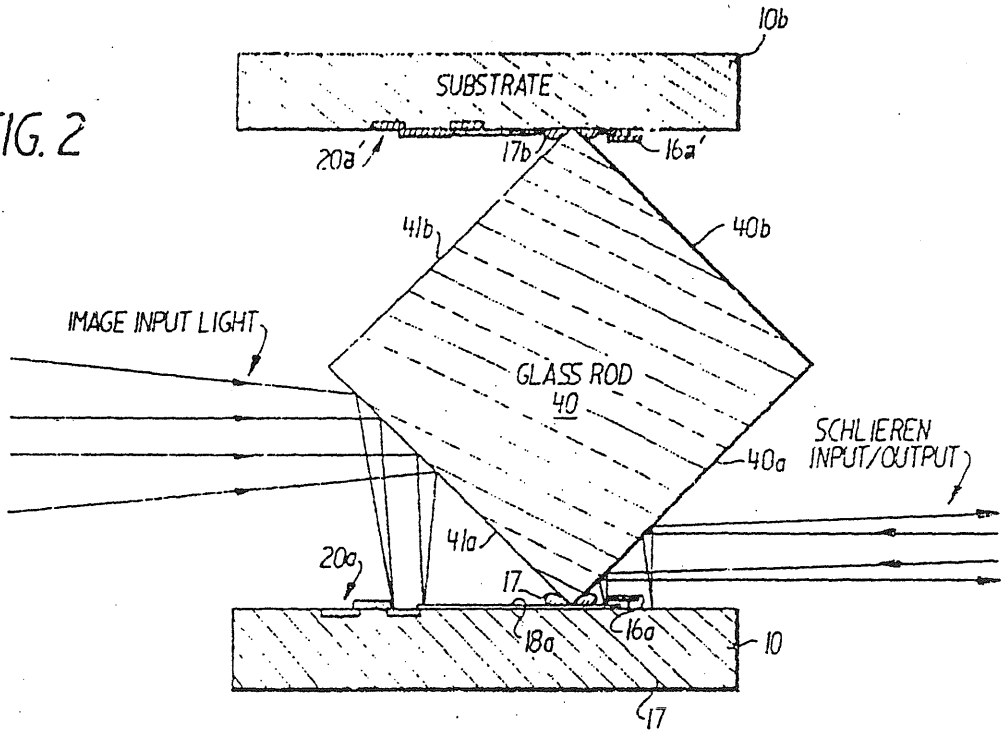
7. The radiation generator of claim 6 wherein said source of radiation is an elongated source having a sufficient length to enable a portion of the radiation which forms said first radiation pattern to overlap that which forms said second radiation pattern.

8. The radiation generator of claim 6 wherein said source of radiation is a gamma emitter.

9. The radiation generator of claim 6 further comprising a radiation absorber positioned external said shutter means and so located as to interrupt a portion of emitted radiation, said radiation absorber being selectively shaped so as to impart a preselected configuration of radiation.

* * * * *

FIG. 2


10b
SUBSTRATE
20a'
17b
16a'
41b
40b
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GLASS ROD
40
SCHLIEREN
INPUT/OUTPUT
40a
41a
20a
17
18a
16a
10
17

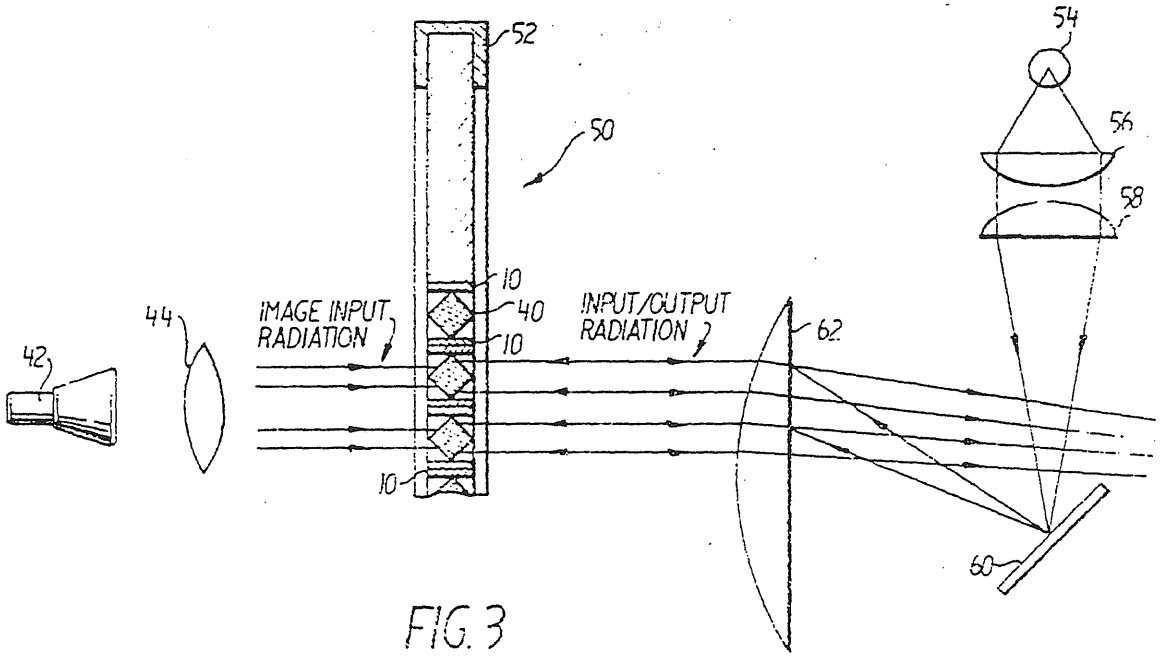

52
50
54
56
58
10
40
10
44
42
IMAGE INPUT
RADIATION
INPUT/OUTPUT
RADIATION
62
10
60

FIG. 3

RADIATION MODULATION APPARATUS

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to apparatus for modulating a source of unmodulated radiation and in particular, to such radiation modulators comprising a plurality of mirror surfaces.

2. Description of the Prior Art

In the prior art, there have been many attempts to develop a satisfactory radiation modulator whereby a source of uniform-intensity radiation is modulated. One contemplated application for such a radiation modulator is a large projection display or a light intensifier panel. It has been sugested to use a relatively thin film of a suitable insulating material, such as an oil or a thermal plastic, upon which a charge pattern is imposed by an electron beam. A source of uniform-intensity light is directed onto the insulating film, whose thickness and therefore whose reflecting properties have been varied in accordance with the charge pattern. The radiation of uniform intensity may be directed upon the insulating film by a Schlieren optical system to be modulated by and reflected from the thin insulating layer to provide an imgage display.

Radiation modulators of the prior art have used a plurality of mirror surfaces whereby radiation from a source is modulated dependent upon the position of the mirror surfaces with respect to its source. By deflecting selected mirror surfaces, selected portions of the radiation image are directed from the line of view, whereas the remaining mirror surfaces direct the radiation along a line to be displayed or to be viewed. In one example of the prior art, a plurality of mirrors may be mounted upon a filament to be rotated by an armature coil. The problem associated with such radiation reflectors is that of resolution and of providing a sufficient number of mirror surfaces capable of achieving a high resolution.

More recently, modulating apparatus has been proposed in which a plurality of stretched membranes are used as mirror surfaces and are bent or deformed under the influence of an electric field established by relatively high deformation voltages. However, because of the high tensile restoring forces established by the stretched membranes, it is necessary to use relatively high voltages to deform or deflect the stretched membranes. With voltages of reasonable amplitude, the deformation of such membranes is in the order of a wavelength of light so that only phase modulation of coherent light is possible. As a result, such devices incur the small tolerances and other problems of optical phase modulators. Typically, the deformation voltage required of modulators employing stretched membranes is in the order of 5000V. It is recognized that optical amplitude modulation systems are easier to operate reliably, but require significant mirror deflection.

SUMMARY OF THE INVENTION

It is therefore, an object of this invention to provide optical amplitude modulation apparatus capable of operation at signal levels significantly less than that required by the prior art.

It is a further object of this invention to provide radiation modulating apparatus employing a plurality of reflecting or mirror surfaces, capable of achieving a greater resolution than apparatus of the prior art.

It is even a further object of this invention to provide radiation modulating apparatus capable of modulating a source of radiation of a first type in accordance with a radiation image of a different type; for example, coherent radiation may be modulated in accordance with a non-coherent radiation image.

These and other objects are met in accordance with the teachings of this invention by providing radiation modulating apparatus comprising at least one reflective surface or mirror capable of being deflected to modulate radiation of substantially uniform intensity derived from a first source. The deflection of the mirror surface is effected by an electric field established by a signal imposed upon an electrode disposed adjacent to the mirror surface. The deflection signal is provided by a radiation sensitive device, such as a photodiode, disposed to receive input radiation from a second source. A dual purpose member is disposed to block radiation derived from the first source from being directed onto the radiation sensitive device, and to direct radiation from the first source to and from the mirror surface, as well as to direct radiation from the second source onto the radiation sensitive device. Thus, the radiation from the first source is modulated in accordance with the input radiation directed onto the radiation sensitive device, whose output in turn controls the deflection of the mirror surface.

A significant feature of this invention resides in the incorporation of a plurality of such mirror surfaces and radiation sensitive devices into an array, whereby the radiation from the first source is modulated by the mirror surfaces to form an image for display in accordance with an input radiation image directed onto the corresponding radiation sensitive devices.

A still further feature of this invention resides in the implementation of the above-described radiation modulator in the form of a semiconductor substrate in which there is formed the radiation sensitive device as a photodiode, and upon which the reflective surface is formed of a layer of a suitably reflective material such as gold, supported upon the substrate by a pedestal. The dual-purpose barrier member may illustratively take the form of a glass rod disposed between the photodiode and the reflective surface. A linear array of the radiation sensitive devices and corresponding reflective surfaces may be formed upon a common substrate and a plurality of such substrates may be assembled to form a two-dimensional array whereby uniform intensity radiation is modulated in accordance with an input radiation image.

DESCRIPTION OF THE DRAWINGS

These and other objects and advantages of the present invention will become more apparent by referring to the following detailed description and accompanying drawings, in which:

FIG. 1A and 1B are respectively a plan and sectioned view of an assembly incorporating a radiation sensitive device whose output controls the deflection of a reflective or mirror surface in accordance with the teachings of this invention;

FIG. 2 is a side view of an assembly as shown in FIG. 1, incorporating a glass rod for directing an input radiation image onto the radiation sensitive device and for directing a uniform-intensity radiation to and the mirror modulated radiation from the mirror surface; and

FIG. 3 is a schematic illustration of the arrangement of a plurality of the assemblies as shown in FIG. 2 to provide an array of radiation sensitive devices disposed to receive an input radiation image for providing a plurality of signals to control the deflection of an array of mirror surfaces whereby substantially uniform intensity radiation is modulated in accordance with the input radiation image.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

With regard to the drawings and in particular to FIGS. 1A and 1B, there is shown an assembly 10 for receiving a radiation sensitive device 20*a* whose output is applied by a conductive element or strip 18*a* to control the deflection of a reflective or mirror surface 16*a*. As will be explained later, suitable means is provided for directing input radiation onto the radiation sensitive device 20*a* and also for directing uniform-intensity radiation onto the mirror surface 16*a*. In the illustrative embodiment shown in FIG. 1A and 1B, the assembly 10 comprises a substrate 17 of a suitable semiconductive material, such as silicon, upon which there is disposed a first insulating layer 12 made of a suitable material, such as silicon dioxide SiO_2. A reflective surface indicated in FIG. 1B by the numeral 16*a* is supported upon the surface of the assembly 10 by a pedestal 14*a*. In an illustrative method of manufacture, a layer of a suitable material such as silicon, is sputtered upon the surface of the insulating layer 12. Next, a layer of a suitable reflective material, such as gold, having a thickness permitting deflection at relatively low signal levels, is deposited as by well-known evaporation techniques, upon the silicon layer. Thereafter, the circumferential portions of the silicon layer are removed by suitable, well-known etching techniques to leave the pedestal portion with a substantially flat, reflective layer 16a disposed thereon. A reflective layer 16*a* having a thickness of 0.25μm was found to be a thickness permitting deflection of approximately 4° when a signal developed by the radiation sensitive device 20*a* of below 100v amplitude is applied to the conductive strip 18*a*.

In the illustrative embodiment shown in FIG. 1B, the radiation sensitive device 20*a* is illustratively shown as a MOS transistor comprising a drain region 22 and a source region 26*a* formed by well-known diffusion techniques within the substrate 17, the regions 22 and 26*a* being of a conductivity type opposite to that of the substrate 17. A channel 24 is formed between the regions 22 and 26*a* and a gate electrode 30 is disposed upon a second insulating layer 28 formed upon a portion of the surface of the substrate 17, covering the channel 24. The output of the radiation sensitive device 20*a* is coupled to the conductive strip 18a by an electrically conductive region 27 formed, for example, by diffusing a high density of impurities of the same type as regions 22 and 26*a* into the silicon substrate 17. Though in FIG. 1B, a MOS transistor has been formed in the substrate, it is operated as a photodiode comprising region 26*a* and the substrate 17, in a manner to be explained more fully below. Further, it is understood that other radiation sensitive devices could be incorporated into the radiation modulator of this invention; for example, a phototransistor may be formed readily upon the substrate 17.

With regard to FIG. 1A, there is shown an illustrative arrangement by which a linear array of the radiation sensitive devices 20 may be formed for controlling a corresponding linear array of mirror surfaces 16. More specifically, each of the radiation sensitive devices takes the form of a MOS transistor comprising a common drain and common gate electrode 22 and 30, both disposed along the length of the assembly 10, and discrete, individual source electrodes 26*a*, 26*b*, 26*c*, etc., for each of the radiation devices 20. A plurality of conductive strips 18*a*, 18*b*, 18*c*, etc. are each connected to their corresponding source region 26 for applying their output to a corresponding electrode 19*a*, 19*b*, 19*c*, etc., for establishing an electrical field for deflecting the corresponding mirror surface 16. The mirror surfaces 16 are formed of a common reflective layer having opposing portions 15 removed therefrom to form each mirror surface 16 capable of being separately deflected. As indicated by a dotted line in FIG. 1A, the pedestal portions 14 are of substantially circular configuration and are centrally disposed of each of the mirror surfaces 16.

The operation of the assembly 10 in a "storage mode" will now be explained with regard to FIGS. 1A and 1B. A pulse source 31 applies a reset pulse to the common gate electrode 30 to reset all of the photodiodes and conductive strips 18 to a "black 'on' signal" condition. Upon being reset by the pulses derived from the source 31, a field is established by the electrodes 19 upon their corresponding reflective surfaces 16, which are deflected to their maximum. More specifically, the reset pulse momentarily turns the MOS transistor "on" to permit conduction across each of the channels 24 to apply a potential illustratively in the order of −50V, from a potential source 32 connected to the common drain electrode 22, to each of the photodiodes formed by the discrete source regions 26*a*, 26*b*, 26*c*, etc. Then, with the radiation sensitive devices 20 shielded from radiation, a voltage is set upon the common gate electrode 30 by a voltage source 33 to turn "off" the MOS transistors, i.e. no current is conducted through the channels 24 thereof. Then, the array of radiation sensitive devices is exposed to an input image for a short period of time by a shutter (not shown). The photocharge that flows in particular photodiode depends upon its exposure, i.e. the product of the intensity of the input radiation and the exposure interval. As one of the photodiodes is exposed, the potential stored in the inherent capacitance of the photodiode is discharged toward a positive voltage imposed upon the substrate 18 by a potential source 34, illustratively of a value of +50V. As a result of the photodiode discharge, the potential established by the conductive strips 18 upon the electrodes 19 changes, whereby the degree of deflection of the corresponding mirror surface 16 is changed, dependent upon the signal established upon the corresponding electrode 19 and the radiation incident upon the corresponding radiation device 20. By employing the voltage sources 32 and 34 in the arrangement shown in FIGS. 1A and 1B, a half-full voltage biases the mirror or reflective surface 16 to a one-quarter bend because of the square law mirror bending response. This circuit arrangement requires less switching voltage; however, the photodiode still must withstand the full voltage, i.e., 100V. The biasing voltages established upon the electrodes 19*a*, 19*b*, 19*c*, etc. remain as a stored pattern until they decay through the photodiode dark current, or until they are erased by a reset pulse derived from the source 31.

In an alternative mode of operation of this invention termed a "continuous mode", the MOS transistors comprised of the regions 22, 24 and 26 are biased to a triode condition. The input radiation induces a photocurrent supplied through the MOS channels 24 associated with the particular photodiode formed of the corresponding region 26. The photocurrent determines the output established upon the discrete source region 26, which is connected to the corresponding electrode 19. Thus, the electrode voltage is a function of the photocurrent of a particular radiation sensitive device and changes with time as the intensity of the input radiation changes.

The complete operation of the radiation modulator of this invention will become more fully understood when considered with FIG. 2. More specifically, FIG. 2 shows an assembly 10 as described above with regard to FIGS. 1A and 1B, in combination with a reflecting member 40 illustratively taking the form of a glass rod having a first highly-reflective specular surface 40*a* for directing substantially uniform radiation onto the linear array of mirror surfaces 16 and for reflecting therefrom the radiation as modulated by the deflected mirror surfaces 16. The reflective member 40 serves the further purpose of isolating the uniform radiation as dervied from a first source, from the input section of this invention, including the radiation sensitive devices 20. The input radiation as derived from a second source is directed by a specular reflective surface 41a onto the photodiode portion of the radiation sensitive device 20. As will be explained more fully later, it may be desirable to form a similar assembly 10*b* disposed in an opposing relationship to the assembly 10, whereby radiation derived from the second source is reflected by a surface 41*b* of the member 40 onto a second linear array of radiation sensitive devices, one of which is indicated by the numeral 20*a'*, for controlling the deflection of a second array of mirror surfaces, one of which is indicated by the numeral 16*a'*.

With regard to FIG. 2, the reflecting member 40 may illustratively take the form of a glass rod secured to the assemblies 10 and 10*b* by suitable insulating adhesives 17 and 17*b* disposed between the reflective member 40 and the assemblies 10 and 10*b*. The insulating adhesives 17 and 17*b* are used to prevent the shorting of adjacent conductive strips 18. In an illustrative embodiment of this invention, the spacing of the reflective member 40 from the radiation sensitive devices is large, as compared to the diffusion length of the photodiodes; further, the silicon substrate may be doped so that a barrier layer attenuates carrier diffusion from the reflective side to the radiation sensitive device side of the assembly. Barrier geometries are also possible and may be employed if more attenuation is required.

Though in FIGS. 1A and 1B, and 2, a preferred embodiment of this invention is shown as including an assembly including a semiconductor substrate and a reflective member 40 for optically isolating the reflective surfaces and the radiation sensitive devices, an alternative embodiment of this invention may be structured including an opaque, multilead plate having a photodiode or a plurality of photodiodes disposed upon a first surface thereof and a plurality of leads directed through the plate for controlling a corresponding mirror surface or set of mirror surfaces formed upon the opposite side of the multilead plate. Illustratively, the multilead plate may be made of opaque glass with conductive lead wires embedded therethrough. Alternatively, the multilead plate may be comprised of a crystal of silicon doped by diffusion through the thickness of the crystal plate to form the leads.

With regard to FIG. 3, there is shown a further embodiment of this invention in which a plurality of the assemblies shown in FIG. 2 are "stacked" upon each other to form a matrix of mirror surfaces 16 capable of modulating an image. A plurality of units comprising assemblies 10 and 10*b* with a reflective member 40 are arranged one upon each to form a composite assembly 50 having an input face disposed to receive an input radiation image derived from a suitable image source such as a CRT 42. The CRT 42 displays an image upon the face thereof which is directed by a lens assembly schematically shown and identified by numeral 44 onto the input face of the composite assembly 50. More specifically, the input image radiation is directed and focused onto the plurality of reflective members 40 whereby discrete portions thereof are directed onto the plurality of radiation image devices 20 to produce output signals for controlling the corresponding mirror surfaces 16 disposed in an array upon the output face of the composite assembly 50. The plurality of individual assemblies are held together by a frame 52 disposed about the periphery of the composite assembly 50; further, the end portions of the assemblies 10 and 10*b* as well as the reflective members 40 may be configured to fit within the frame 52, whereby the assemblies 10 and 10*b* and in particular the reflective members 40 are critically aligned with respect to the input radiation derived from the CRT as well as the uniform intensity radiation derived from a source 54. Alternatively, the image source may be a hologram formed by coherent light from a laser.

In the illustrative embodiment shown in FIG. 3, a Schlieren-type optical system is shown for projecting an image of substantially uniform intensity radiation from the source 54 onto the output face of the composite assembly 50. Any of the several well-known Schlieren optical systems may be used of which one simple illustrative one is as follows. The radiation emitted by the source 54 is focused by a pair of planar-convex lenses 56 and 58 onto a mirror 60. The reflected radiation from the mirror 60 is focused by a planar-convex lens 62 onto the output face of the composite assembly 50, whereby the uniform-intensity radiation is directed by the plurality of the reflective members 40 onto their associated mirror surfaces 16. As explained above, each mirror surface 16 of the composite assembly 50 is deflected in accordance with the input radiation image so that incremental portions of the uniform radiation image directed onto the array of mirror surfaces are variously modulated dependent upon which of the mirror surfaces is deflected. If a mirror surface is deflected, the radiation directed thereto from the reflective member 40 will be misdirected so that it is intercepted by a stop, which may be the mirror 60, thus incremental portions of the image as derived from the composite assembly 50 will appear dark or black. Upon being reflected from the array of mirror surfaces, the modulated portions of the image are reflected from the corresponding members 40 onto the lens 62 to be focused, for example, to provide a display or for direct view.

Significantly, the radiation modulating apparatus shown in FIG. 3 may be used as a light amplifier. For

example, the intensity of the light flux derived from the source 54 may be many times greater than that derived from the input image source 42. As a result, the original, low-intensity radiation image input is amplified many times. Further, the source 54 may emit a different type of radiation than that derived from the source 42. For example, the source 54 may illustratively take the form of a laser for generating coherent light onto the output face of a composite assembly 50, whereas the source 42 may be a CRT for directing a non-coherent, relatively low-intensity radiation image onto the input face of the composite assembly 50. In such an example, the composite assembly 50 modulates the coherent parallel beam of light derived from the laser to reflect therefrom a hologram to be used, for example, in an optical data processing system, the hologram being modulated by the mirror deflection pattern. In this example, the input radiation image is both non-coherent and of low light level so that no hologram could be formed thereby for effective image processing. However, the composite assembly, in accordance with the teachings of this invention, provides both image intensification and radiation conversion to provide a coherent modulated output.

In an illustrative embodiment of the composite assembly 50 as shown in FIG. 3, an array of mirror surfaces, each having a surface area of approximately $25\mu m^2$ wide, is formed along a linear array upon the assemblies 10 and 10*b* with a 50μm center-to-center spacing. The reflective members 40 may take the form of mirror rods having a square cross-section with a 250μm diagonal so that the linear arrays as formed of assemblies 10 and 10*b* are spaced two per 300μm. Such a composite assembly would have a resolution of 3–lp/mm along the linear array (a direction normal to the surface of FIG. 3) and 10–lp/mm in a second, substantially vertical direction, as shown in FIG. 3. Further, in this illustrative embodiment, the thickness of the mirrors 16 was chosen to be 0.25μm. Though mirrors of 0.45μm have been constructed, the smaller thickness of 0.25μm is preferred because of the reduced pull-in voltage required. Further, as particularly illustrated in FIG. 1B, the close spacing and aspect ratio of the mirror surface as a cantilever beam tend to reduce the pull-in voltage whereby relatively reasonable voltage levels, less than 10V, may be employed.

Thus, there has been shown a radiation modulating apparatus employing a plurality of mirror surfaces disposed in an array and capable of selectively modulating substantially uniform radiation derived from a first source in accordance with the various deflections imposed upon the mirror surfaces. Mirror deflection is controlled, in turn, by an input radiation image directed onto a corresponding array of radiation sensitive devices whose outputs are applied to control the deflection of the mirror surfaces. Further, suitable barrier means such as reflective mirrors are disposed between the radiation sensitive devices and the mirrors, which serves not only to isolate the radiation derived from the first source from the radiation sensitive devices, but also to direct the input radiation onto the radiation sensitive devices and to direct the uniform intensity radiation derived from the first source onto and the modulated radiation from the mirror surfaces to be displayed or for direct view.

Numerous changes may be made in the above-described apparatus and the different embodiments of the invention may be made without departing from the spirit thereof; therefore, it is intended that all matter contained in the foregoing description and in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

What is claimed is:

1. Apparatus for modulating radiation derived from a first source in accordance with input radiation derived from a second source, said apparatus comprising:
   a. means responsive to the input radiation and disposed to receive the input radiation for providing an output dependent upon the intensity of the input radiation;
   b. mirror disposed to receive the radiation from said first source;
   c. means for mounting said mirror in cantilever fashion, to permit a free end of said mirror to be deflected;
   d. conductive means coupled to receive the output of said radiation responsive means for establishing a field in the vicinity of said mirror, whereby said mirror is deflected dependent upon the output of said radiation responsive means; and
   e. means for isolating said radiation sensitive means from the radiation derived from said first source.

2. Apparatus as claimed in claim 1, wherein said radiation responsive means and said mirror are mounted upon a common substrate, and said isolating means is disposed intermediate therebetween.

3. Apparatus for modulating radiation derived from a first source in accordance with input radiation derived from a second source, said apparatus comprising:
   a. means responsive to the input radiation and disposed to receive the input radiation for providing an output dependent upon the intensity of the input radiation;
   b. a mirror deflectively mounted to receive the radiation from said first source, said mirror being variably deflected dependent upon the output of said radiation responsive means whereby the radiation derived from said first source is modulated; and
   c. means for isolating said radiation sensitive means from the radiation derived from said first source and comprising a reflective member disposed between said radiation sensitive means and said mirror, said reflective member comprising a first reflective surface for directing the input radiation to said radiation responsive means, and a second reflective surface for directing the radiation derived from said first source to and the modulated radiation from said mirror.

4. Apparatus as claimed in claim 3, wherein said first source provides radiation of a first level of intensity and said second source provides radiation of a second level of radiation less than that of the first level.

5. Apparatus as claimed in claim 3, wherein said first source emits coherent radiation and said second source emits non-coherent radiation.

6. Apparatus for modulating radiation derived from a first source in accordance with an input radiation image derived from a second source, said apparatus comprising:
   a. a plurality of radiation responsive devices disposed to receive the input radiation image and for providing corresponding outputs dependent upon the intensity of the input radiation image;

b. a plurality of corresponding mirrors disposed to receive the radiation from said first source, each of said mirrors being variably deflected dependent upon the output of its corresponding radiation responsive device whereby the radiation derived from said first source is modulated in accordance with the input radiation image, each of said radiation responsive devices and mirrors being mounted upon a common substrate;

c. each of a plurality of conductive elements for receiving the output of a radiation responsive device for establishing a deflecting field in the vicinity of its corresponding mirror; and

d. means disposed intermediate of said plurality of radiation responsive devices and said plurality of mirrors for isolating said plurality of radiation responsive elements from the radiation derived from said first source.

7. Apparatus as claimed in claim 6, wherein a plurality of said units is arranged with respect to each other to form a first two-dimensional array of said radiation responsive means disposed to receive an image of the input radiation, and a second two-dimensional array of said mirrors disposed to receive the radiation of substantially uniform intensity from said first source and to modulate the uniform-intensity radiation in accordance with the various degrees of deflection of said plurality of mirrors.

8. Apparatus as claimed in claim 7, wherein there is included a Schlieren optical assembly for projecting the radiation derived from said first source onto said second two-dimensional array of mirrors and for directing the modulated radiation therefrom.

9. Apparatus for modulating radiation derived from a first source in accordance with input radiation derived from a second source, said apparatus comprising:

a. means responsive to the input radiation and disposed to receive the input radiation for providing an output dependent upon the intensity of the input radiation, said radiation responsive means comprising a semiconductor substrate of a first conductivity type and a first region formed within a surface of said substrate of a second conductivity type opposite to said first conductivity type;

b. a mirror deflectively mounted to receive the radiation from said first source, said mirror being variably deflected dependent upon the output of said radiation responsive means whereby the radiation derived from said first source is modulated, said mirror being deflectively mounted upon said surface of said substrate by a pedestal; and

c. means for isolating said radiation sensitive means from the radiation derived from said first source.

10. Apparatus as claimed in claim 9, wherein said mirror comprises a layer disposed upon said pedestal having a reflective surface for receiving the radiation from said first source and of a thickness sufficient to facilitate deflection to a sufficient degree to permit optical modulation.

11. Apparatus as claimed in claim 10, wherein the thickness of said layer is in the order of 0.25μm.

12. Apparatus as claimed in claim 9, wherein said radiation responsive means comprises said first region and a second region of said second conductivity type separated by a channel formed of a portion of said substrate, and a gate electrode disposed over said chanel and spaced therefrom by an insulating layer.

13. Apparatus as claimed in claim 12, wherein a plurality of radiation responsive means is formed upon said substrate in a linear array, each of said radiation devices comprising a common second region and a common gate electrode and discrete first regions for each of said radiation responsive means.

14. Apparatus as claimed in claim 13, wherein there is included a plurality of said mirrors disposed in a linear array upon said substrate, and a plurality of conductive strips coupled to said discrete first regions of said radiation responsive means for applying discrete outputs thereof to control independently the deflection of each of said plurality of mirrors in accordance with the input radiation directed onto each of said plurality of radiation responsive means.

* * * * *

RADIATION DETECTORS AND DEMODULATORS

July 6, 1937. P. T. FARNSWORTH 2,085,742

ELECTRON IMAGE AMPLIFIER

Filed June 14, 1930 2 Sheets-Sheet 1

Fig. 1.

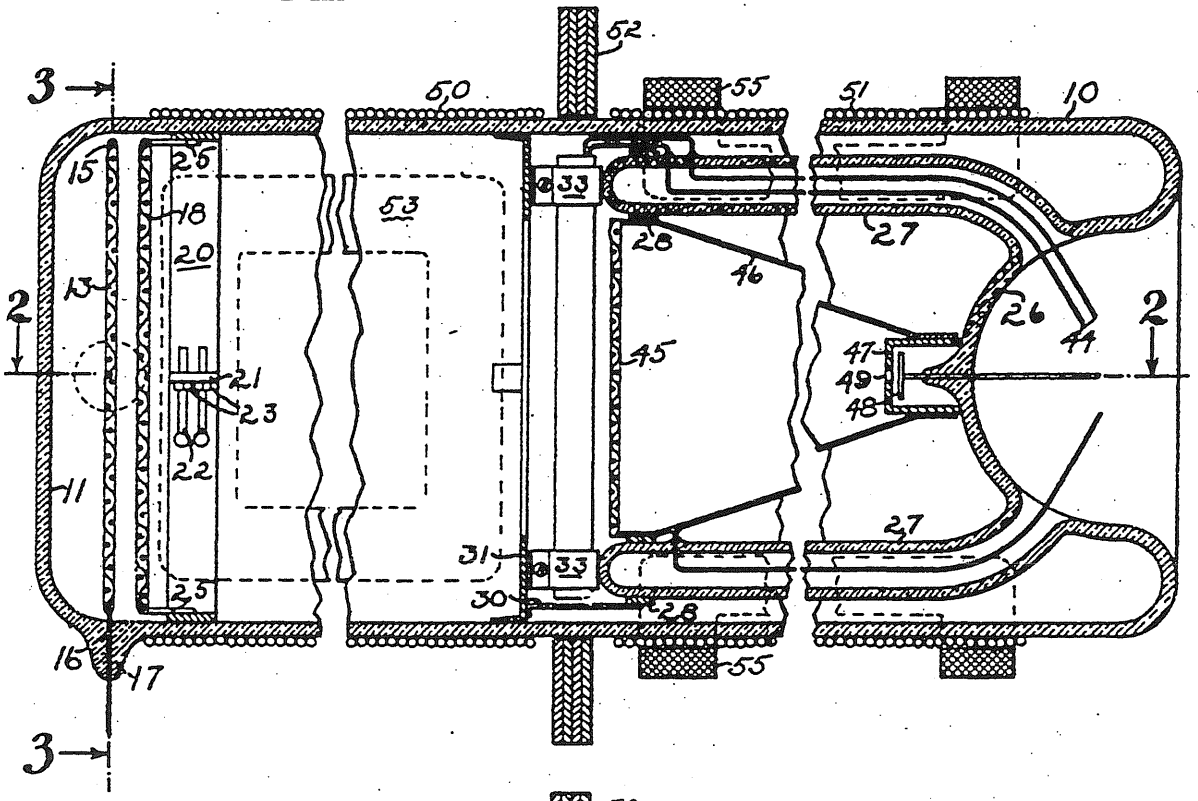
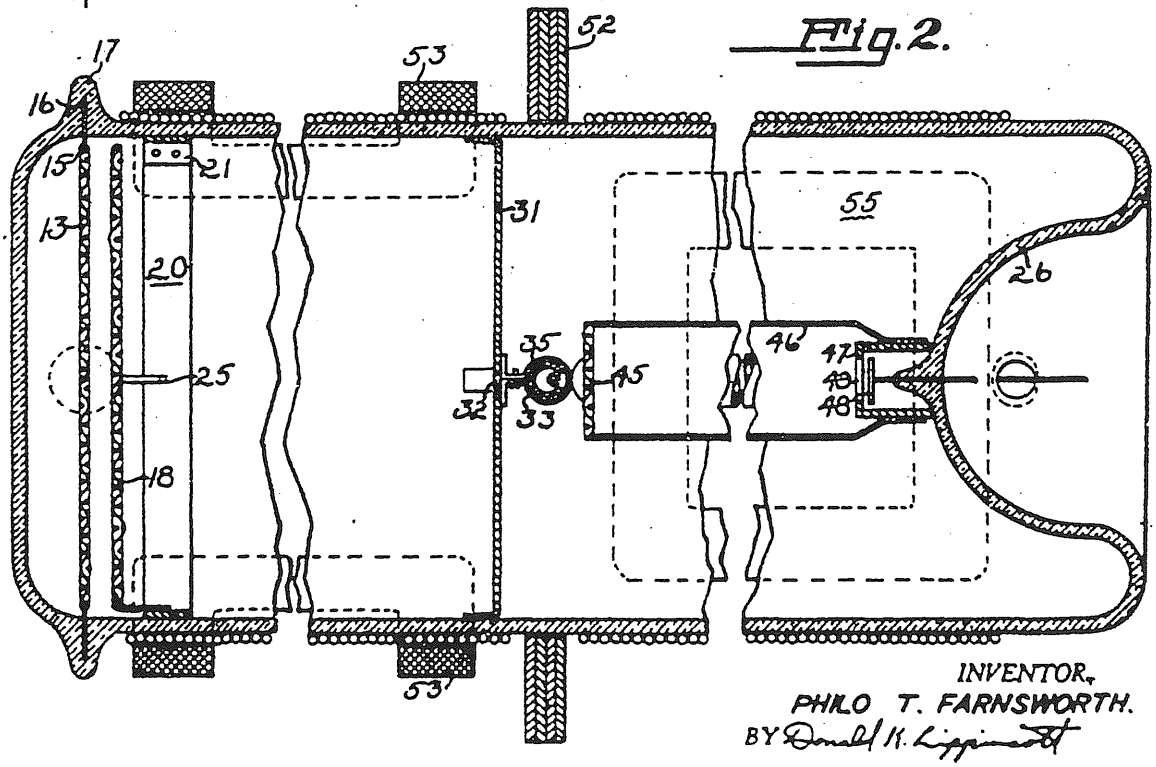


Fig. 2.



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ELECTRON IMAGE AMPLIFIER

Filed June 14, 1930 2 Sheets-Sheet 2

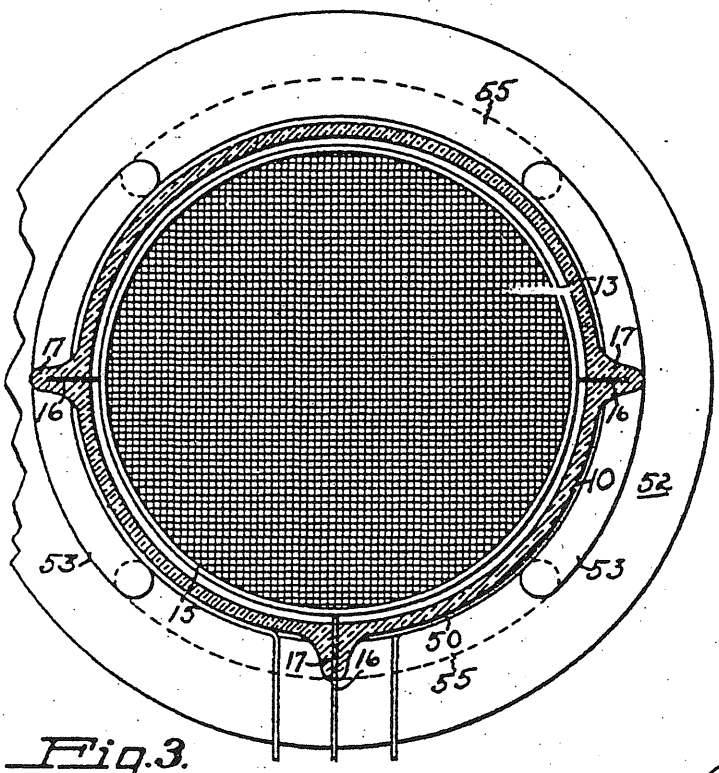


Fig. 3.

Fig. 4.

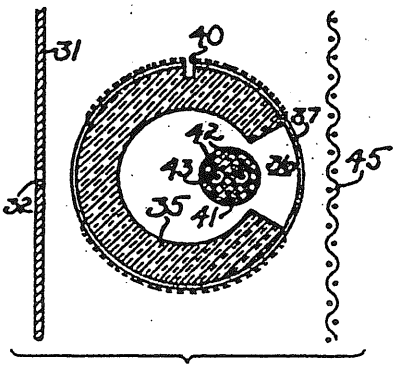


Fig. 5.

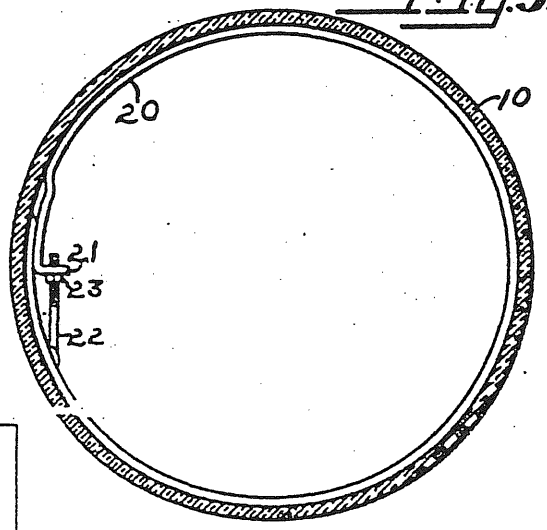
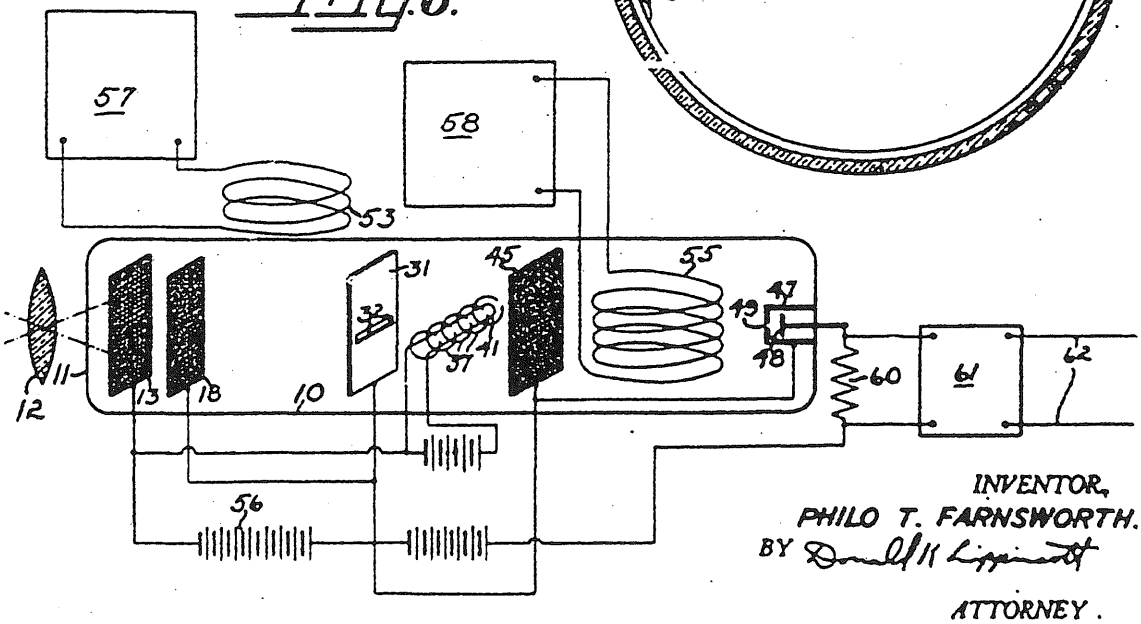


Fig. 6.



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2,085,742

ELECTRON IMAGE AMPLIFIER

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Application June 14, 1930, Serial No. 461,110

32 Claims. (Cl. 178—6)

My invention relates to apparatus for the electrical projection of pictures, as in television, facsimile transmission, and the like, and particularly to such apparatus as is used in connection with electrical scanning systems.

Among the objects of my invention are: First, to provide a method of increasing the sensitivity of television transmission cells to permit the projection of television pictures by reflected light of ordinary intensity; second, to increase the electrical output of a television cell in order to provide satisfactory television signals without the use of extremely sensitive amplifiers; third, to provide a television system wherein an amplification of an electrical image, or a portion thereof, may be accomplished without dissecting said image into picture elements; fourth, to provide a method of amplification for television purposes wherein the degree of amplification is not limited by the extremely high frequencies which must be handled where the image is dissected before amplification; fifth, to provide a means whereby relatively large currents may be secured from a television transmitting cell without interference from space charge effect; sixth, to provide an image amplifying element which is simple and practical to construct; and seventh, to provide an amplifier for photo-electric currents wherein extremely high amplifications may be obtained with extremely simple apparatus external to the tube itself, and in a single stage.

My invention possesses numerous other objects and features of advantage, some of which, with the foregoing, will be set forth in the following description of my invention. It is to be understood that I do not limit myself to this disclosure of species of my invention, as I may adopt variant embodiments thereof within the scope of the claims.

In my previous co-pending applications for United States Letters Patent, including applications Serial No. 159,540, filed January 7, 1927 (Patent No. 1,773,980), Serial No. 245,334, filed January 9, 1928, and Serial No. 270,673, filed April 17, 1928, I have described a television transmitting apparatus and system wherein an optical image of the pictured field is thrown upon a photo-sensitive cathode, and the emitted electrons are accelerated and focused magnetically to form an electrical image, i. e., a plane through which an electron stream passes, the electron density of which varies spatially across the stream in the same manner as the illumination density varies across the optical image. In this specification and claims the terms "electrical image", or, more specifically "electron current image", will therefore be used to indicate an electron stream wherein the current density is simultaneously proportional and corresponds in relative position to a plurality of adjacent elementary areas of a corresponding optical image.

The electron stream forming this image may be deflected, preferably by magnetic means, to pass over an aperture in such a manner as to effect a scanning of the image, that portion of the electron stream which passes through the aperture forming a picture current which may be amplified and modulated upon a radio wave or transmitted by wire.

This method of television transmission offers the advantage of having no moving parts, and of being suitable for the electrical projection of pictures having any desired fineness of detail.

The principal weakness of this method lies in the fact that only a relatively small portion of the electrons emitted from the photo-sensitive surface are used at any given instant, and therefore extremely photo-sensitive screens and amplifiers are necessary in order to transmit satisfactory pictures.

When it is attempted to amplify the picture currents above a certain level, background noise, "Schottke effect" and other ordinarily negligible factors come in to make the amplified picture currents unsatisfactory and distorted.

In the present invention the fundamental principle of my previous invention is retained, i. e., an electrical image corresponding to the optical image is formed; in the present device, however, instead of first dissecting the image into picture elements and amplifying the resultant current, a plurality of picture elements are simultaneously amplified before the image is dissected, or, at least, before it is completely dissected.

Describing this invention in general terms, means are provided for forming an electrical image of the pictured field as in my previously described devices. The electrical image, or a portion thereof, is received upon a plurality of isolated control elements, which regulate the electron flow from a second cathode, preferably of the thermionic type, to form a secondary electrical image which varies in consonance with the primary image. In the preferred form of the device the primary electrical image is deflected in accordance with a predetermined time schedule, preferably at the low, or "picture frequency" scanning rate, across a linear aperture in a diaphragm situated substantially in the focal plane of the electrical image. The aper-

tured diaphragm may be termed an "electrical shutter." The thermionic cathode is also linear, extending back of and parallel with the linear aperture. Encircling the cathode is a winding comprising discontinuous turns of very fine wire, each turn forming in effect a grid or control electrode whose potential is determined by the number of electrons reaching it through the aperture of the diaphragm. An anode screen positioned adjacent the linear cathode accelerates the electrons which it emits, these electrons being focused as in the case of the primary image in a second focal plane, and since the potential of the isolated control elements varies spatially in consonance with the primary electrons falling upon them, a very greatly amplified secondary image is formed.

Where this device is being used for its primary purpose, i. e., as a television transmitter, the secondary image is deflected, in the direction of its length and at the high scanning frequency of the picture to be transmitted, across an aperture behind which a target for receiving electrons is positioned. The electrons flowing upon this target comprise a picture current, which may be amplified as has previously been described in my above mentioned applications.

Owing to the extremely small capacity of the elementary control electrodes which govern the formation of the secondary image, and owing to the fact that these elements vary in potential at a much lower rate than the higher picture component frequencies which must be transmitted, extremely high amplifications are obtainable from the device, the secondary electron image having an electron density 10,000 or more times as great as that of the primary image. This makes it possible to transmit pictures by reflected light, or, where it is desired to transmit pictures from moving picture film greatly to reduce the amplification necessary external to the transmitting apparatus.

Referring to the drawings:

Figure 1 is an axial sectional view of a television transmitting tube embodying my invention.

Figure 2 is a similar sectional view, the plane of section being perpendicular to that of Figure 1, as indicated by the line 2—2 of the first figure.

Figure 3 is a transverse sectional view, taken in the plane indicated by the line 3—3 of Figure 1.

Figure 4 is an enlarged detail section of a portion of Figure 2.

Figure 5 is a transverse sectional view showing the expanding ring for supporting the anode.

Figure 6 is a schematic diagram showing the principal electrical circuits used in connection with the device.

In detail, a preferred embodiment of my invention comprises an envelope 10, of substantially tubular form, having at one end a substantially flat window 11 through which an optical image may be projected by a suitable lens 12. In a position closely parallel to this window is a photosensitive cathode, comprising a screen 13 of fine wire netting, stretched on a ring 15 which is supported by radial wires or pins 16 secured to the envelope by seals 17. Deposited upon the screen is a suitable photo-active material such as potassium hydride, caesium, or other suitable medium.

Parallel and closely adjacent to the cathode is the similar anode screen 18, preferably of finer wire than the cathode screen. The anode may be supported upon an expanding ring comprising a strap 20, one end of which is bent inward to form a flange 21. A pair of small bolts 22, welded to the other end of the strap, engage holes in the flange, and by tightening the nuts 23, the ring is expanded into frictional engagement with the wall of the envelope. Support wires 25 are welded to the anode screen and to the expanding ring to hold the screen in position.

The inner surface of the envelope is preferably platinized or silvered from the expanding ring back to the opposite end of the tube, and the ring makes contact with the metallic surface, which thus provides an equipotential space through which the electrons may travel after being accelerated from the cathode by the anode.

A stem 26 is sealed into the end of the envelope opposite to the window, and carries a pair of arms 27 which project substantially half the length of the envelope and closely adjacent its walls. Surrounding the ends of each of these arms is a band 28, welded to each of which is a wire 30 for supporting a diaphragm 31. A linear slit 32 extends across the diaphragm.

The image amplifier element is mounted on the diaphragm behind the slit, by means of the collars 33. This element comprises a tube 35, formed of porcelain or other suitable refractory insulating material, and having a longitudinal slot 36 formed in the side opposite the diaphragm. The tube is wound with fine wire 37. In one of these devices which I have constructed, this winding comprises tungsten wire, .0003 inch in diameter, and wound 240 turns to the inch.

After the tube is wound the winding is partially coated with material for insulating it and connecting it to the porcelain tube. This insulating material may be vitreous enamel, alundum cement, or other suitable refractory. In applying the cement, that portion of the winding immediately behind the slit in the diaphragm is left bare, as is that portion covering the slot 36. After the cement coating has set a saw-cut 40 is made, extending the length of the tube, to separate the winding into individual discontinuous turns.

A thermionic cathode 41 extends the length of the tube behind the slot 36. This cathode may be formed of a silicon rod having a pair of parallel perforations 42 extending the length thereof, and a filamentary heater 43 threaded through the perforations. The exterior of the rod is first platinized, then coated with alkaline-earth oxide or other suitable electron emitting material, and is grounded to one end of the heater 43. A pair of leads 44 for supplying current to the heater is carried out of the envelope through one of the arms 27.

A second anode 45, also of screen construction, is supported from the bands 28 closely adjacent to the slot 36. The anode covers, and is electrically continuous with a flat, funneled shaped shield 46 whose smaller end terminates adjacent the stem 26 in an inner shield or capsule 47. The capsule covers a target 48, and is provided with an aperture 49 which is preferably an elongated slot which lies in a plane perpendicular to the diaphragm slit 32.

Surrounding the envelope are two solenoidal focusing coils 50 and 51. These coils carry direct current for focusing the electron images as is described in my copending application, Serial No. 270,673 above mentioned. Each electron leaving the cathode, at an angle diverging from the direction of the magnetic field, describes a helical path, returning to tangency with the line of force through its source in the same time as

every other electron. The current in the solenoids is adjusted to bring the planes of tangency, i. e., the electrical image coincident with planes of the scanning apertures 32 and 49 respectively.

The two coils may be replaced by a single coil if desired, but separate coils are preferred since the currents therein may be individually adjusted, so that less accurate spacing of the elements in the transmitting device is required. A magnetic shield 52, which may be built up of rings of Swedish iron or other highly permeable material, preferably surrounds the tube between the two coils. For the sake of clearness, neither the focusing coils nor the shields are shown in the diagram of Figure 6.

On the side of the shield toward the window in the envelope is a pair of deflecting coils 53. It will be noted that these coils cause a deflection of the electron image formed by the photo-sensitive cathode in a direction perpendicular to the slit 32, and are at right angles to the position which they would occupy were the focusing coils 50 and 51 not used. A second set of deflecting coils 55, spaced 90° from the coils 53, is provided on the opposite side of the magnetic shield 52. These coils deflect the secondary image perpendicularly to the primary image deflection. Each set of coils is represented by a single coil in the schematic diagram.

In operation, the optical image is focused upon the cathode 13, which emits electrons in proportion to its illumination. These electrons are drawn through the cathode and accelerated by the potential applied to the anode from the battery or other source 56, most of them passing through the anode screen and traveling longitudinally of the envelope at a high velocity, to be focused in the plane of the diaphragm 31 by the longitudinal magnetic field from the coil 50. The electron image formed in the plane of the diaphragm is deflected across the slit 32, which acts as a scanning aperture, at a frequency of from 12 to 20 cycles per second by means of the magnetic field of the coils 53, which are supplied by an oscillator 57.

The oscillator is preferably a generator of sloped or saw-tooth waves, as is described in the co-pending application of Farnsworth and Lubcke, Serial No. 449,985, filed May 5, 1930. The field thus produced causes the image to travel across the slit relatively slowly in one direction, and then to return to its original position with great rapidity, after which the cycle is repeated.

A portion of the electrons forming the electrical image pass through the slit and are intercepted by the grid wires 37. The individual wires being isolated, and having extremely small capacity, can vary in potential relatively rapidly owing to the leakage through the porcelain tube 35 and the residual gas remaining in the envelope. For example, if the slit is 1/200 as wide as the image, and if a scanning frequency of 20 cycles is used, the maximum frequency with which the wires need vary in potential is 2,000 cycles per second.

Since each turn of the winding 37 is insulated from its fellows, adjacent turns may have widely different potentials, depending upon the number of electrons falling thereon, and therefore the electrons attracted from the cathode toward the secondary anode 45 vary spatially in consonance with the electrons in falling through the slit 32 from the primary electron image. The secondary electron image is, of course, negative; i. e., it has a minimum electron density where the primary image has a maximum density, and vice versa.

The secondary image is, moreover, astigmatic. The electron source is effectively the entire width of the slot 36, and since the individual turns of the winding 37 are substantially perpendicular to this slot, and each governs the electron flow passing its entire length, the image formed is the electrical equivalent of a photographic negative of the slit viewed through a cylindrical lens, i. e., the slit 32 is much broadened as it is represented by the secondary electron image. This may be avoided if desired by making the openings 32 and 36 of the same width, but in general the astigmatic image is a great advantage; the electrons emitted by the thermionic cathode exceed vastly in number those emitted by the photosensitive cathode, and the wider image permits the passage of many more electrons before space-charge effect intervenes.

The astigmatic secondary image is focused by the coil 51 in the plane of the inner shield 47. The image is deflected in the direction of its length by a magnetic field from the coils 55, which are excited by a slope-wave oscillator 58, generating a high scanning frequency, e. g., 4,000 cycles per second. The slit or scanning aperture 50 is positioned parallel to the axis of the astigmatism of the secondary image, and therefore all of the electrons controlled by a single grid wire enter the aperture at one time, to fall upon the target 48. These electrons form the picture current which flows through a resistor 60, causing a potential drop which may be amplified by a suitable repeater 61 and transmitted along a line 62 or modulated upon a radio wave.

It will be understood that the operation of the image amplifying device may be modified materially, following the principles that are well known in ordinary vacuum tube practice. The factors which are most readily controlled to accomplish such modification are the various potentials used.

Thus, if the velocity of the electrons forming the primary image be greatly increased, the grid elements may be made to emit secondary electrons in excess of the primaries. Under these circumstances the grid elements become less negative with greater electron density in the primary electrical image, and the secondary image becomes positive instead of negative.

Moreover, if desired, separate leads may be brought out of the tube for the separate anodes and shields, giving almost unlimited flexibility in so far as potential gradients and electron impact velocities are concerned.

The bias potentials of the isolated control elements are not so directly variable, but these may be controlled indirectly by selecting materials of predetermined conductivity for the tube 35, by altering the potential of its supporting bands, to control leakage therethrough, and by variation of the vacuum to which the tube is pumped.

I claim:

1. The method of electrical picture projection which comprises the steps of forming an electron current image of an object, dissecting said image into strips of elementary width, and applying the strips of said electron charge image to control the intensity distribution of a space current of elongated cross-section to form successive partial images of greater intensity.

2. The method of electrical picture projection which comprises the steps of forming an electron current image of an object, dissecting said

image into successive strips of elementary width, applying the strips of said electron current image control a space current to form corresponding partial electron current images of greater intensity, and dissecting said partial images into elementary areas.

3. The method of electrical picture projection which comprises the steps of forming an electron current image of an object, and utilizing successive portions of said image to control the spatial distribution of an electron flow in consonance with linear strips of elementary width of said electron current image to form a succession of secondary partial electron current images corresponding to said strips.

4. The method of electrical picture projection which comprises the steps of forming an electron current image of an object, deflecting said image in accordance with a predetermined time schedule, intercepting a portion of said image, and utilizing the intercepted portion to control the spatial distribution of an electron flow to form a varying secondary image corresponding to the intercepted portion of said first-mentioned electrical image.

5. The method of electrical picture projection which comprises the steps of forming an electron current image of an object, deflecting said image in accordance with a predetermined time schedule, intercepting a portion of said image, utilizing the intercepted portion to control the spatial distribution of an electron flow to form a varying secondary electrical image corresponding to said intercepted portion, deflecting said secondary image in accordance with a different time schedule, and intercepting a varying portion of said secondary image to effect a scanning of the object.

6. The method of electrical picture projection which comprises the steps of forming an electron current image of an object, deflecting said image in one dimension, intercepting strips of elementary width across said image, controlling the spatial distribution of an electron flow in consonance with the intercepted portion to form a secondary electron current image, and deflecting said secondary image in a second dimension.

7. The method of electrical picture projection which comprises the steps of forming an electrical image of an object, deflecting said image in one dimension, intercepting a linear area of said image, controlling the spatial distribution of an electron flow in consonance with the intercepted portion to form a secondary electron image, and deflecting said secondary image in a direction parallel to its length.

8. In an apparatus for the electrical projection of pictures, means for forming an electrical image, means for selecting a substantially linear area from said image, means for deflecting the image normally to said area to vary the area selected, a substantially linear source of electrons, and means for varying the electron flow from elementary lengths of said source in accordance with the intensity distribution of the selected area to form a secondary image.

9. In an apparatus for the electrical projection of pictures, means for forming an electrical image, means for selecting a substantially linear area from said image, means for deflecting the image normally to said area to vary the area selected, a substantially linear source of electrons, means for varying the electron flow from elementary lengths of said source in accordance with the intensity distribution of the selected area to form a secondary image, and means for deflecting said secondary image in a direction parallel to its length.

10. In an apparatus for the electrical projection of pictures, means for forming an electrical current image, an apertured plate arranged substantially in a plane of said image, an emitter of electrons arranged behind the aperture in said plate, means for deflecting said image across said aperture, a control element positioned to derive its potential from the image elements passing through said aperture and to control electron flow from said emitter in consonance with said potential, and means for collecting said electron flow.

11. In an apparatus for the electrical projection of pictures, means for forming an electrical current image, an apertured plate arranged substantially in a plane of said image, means for causing the aperture in said plate to scan said image, an emitter of electrons arranged behind said aperture, means for collecting the emitted electrons, and a control element positioned to derive its potential from the image elements passing through said aperture and to control electron flow from said emitter in consonance with said potential.

12. In an apparatus for the electrical projection of pictures, means for forming an electrical current image, an apertured plate arranged substantially in a plane of said image, an emitter of electrons of greater than elementary length in at least one dimension, arranged behind the aperture in said plate, means for accelerating the emitted electrons to form a secondary electrical image, and a plurality of isolated control elements positioned to derive their potentials from the image elements passing through said aperture and to control said secondary image in consonance with said potentials.

13. In an apparatus for the electrical projection of pictures, means for forming an electrical current image, an apertured plate arranged substantially in a plane of said image, an emitter of electrons arranged behind the aperture in said plate, means for accelerating the emitted electrons to form a secondary electrical image, a plurality of isolated control elements positioned to derive their potentials from the image elements passing through said aperture and to control said electrons to form a secondary image in consonance with said potentials, a second plate having an aperture therein positioned substantially in the plane of said secondary image, and means for causing said apertures to scan said images.

14. In an apparatus for the electrical projection of pictures, means for forming an electrical current image, an apertured plate arranged substantially in a plane of said image, an emitter of electrons arranged behind the aperture in said plate, means for accelerating the emitted electrons to form a secondary electrical image, a plurality of isolated control elements positioned to derive their potentials from the image elements passing through said aperture and to control said emitted electrons in consonance with said potentials to form a secondary electrical current image, a second plate having an aperture therein positioned substantially in a plane of said secondary image, and means for causing said apertures to scan said images in different directions.

15. An electrical discharge device comprising

an envelope, a photo-sensitive cathode arranged within the envelope, an anode positioned adjacent the cathode to accelerate electrons liberated therefrom to form an electrical image, a diaphragm positioned in the plane of said image and having a linear aperture formed therein, means arranged behind said aperture for forming a secondary electrical image having a predetermined relationship to that portion of the first image entering the aperture, and a target arranged to intercept said secondary image.

16. An electrical discharge device comprising an envelope, a photo-sensitive cathode arranged within the envelope, an anode positioned adjacent the cathode to accelerate electrons liberated therefrom to form an electrical image, a diaphragm positioned in the plane of said image and having a linear aperture formed therein, means arranged behind said aperture for forming a secondary electrical image having a predetermined relationship to that portion of the first image entering the aperture, a target arranged to intercept said secondary image, and means for deflecting each of said images in accordance with a predetermined time schedule.

17. An electrical discharge device comprising an envelope, a photo-sensitive cathode arranged within the envelope, an anode positioned adjacent the cathode to accelerate electrons liberated therefrom to form an electrical image, a diaphragm positioned in the plane of said image and having a linear aperture formed therein, means arranged behind said aperture for forming a secondary electrical image having a predetermined relationship to that portion of the first image entering the aperture, a target arranged to intercept said secondary image, and means for deflecting each of said images in different dimensions in accordance with a predetermined time schedule.

18. An electrical discharge device comprising an envelope, a photo-sensitive cathode arranged within the envelope, an anode positioned adjacent the cathode to accelerate electrons liberated therefrom to form an electrical image, a diaphragm positioned in the plane of said image and having a linear aperture formed therein, means arranged behind said aperture for forming a secondary astigmatic electrical image of that portion of the first image entering the aperture, a target arranged to receive said secondary image, and a shield for said target having an elongated aperture therein arranged parallel to the axis of astigmatism of said secondary image.

19. An electrical discharge device comprising an envelope, a photo-sensitive cathode arranged within the envelope, an anode positioned adjacent the cathode to accelerate electrons liberated therefrom to form an electrical image, a diaphragm positioned in the plane of said image and having a linear aperture formed therein, means arranged behind said aperture for forming a secondary astigmatic electrical image of that portion of the first image entering the aperture, a target arranged to receive said secondary image, a shield for said target having an elongated aperture therein arranged parallel to the axis of astigmatism of said secondary image, and means for deflecting each of said images in dimensions perpendicular to the apertures whereon they fall.

20. An image amplifier element comprising an insulating tube having a longitudinal slot therein, a thermionic cathode mounted longitudinally within said tube, a winding surrounding said tube comprising a plurality of discontinuous turns of wire, and means for retaining said winding in position.

21. An image amplifier element comprising an insulating tube having a longitudinal slot therein, a thermionic cathode mounted longitudinally within said tube, a winding surrounding said tube comprising discontinuous turns of wire smaller in diameter than the elements of the image to be amplified, and means for retaining said winding in position.

22. An image amplifier element comprising an insulating tube having a longitudinal slot therein, a thermionic cathode mounted longitudinally within said tube, a winding surrounding said tube comprising a plurality of discontinuous turns of wire, and an insulating coating partially covering each of said turns and cementing the wire to the tube.

23. An image amplifier element comprising an insulating tube having a longitudinal slot therein, a thermionic cathode mounted longitudinally within said tube, a winding surrounding said tube comprising a plurality of discontinuous turns of wire, and an insulating coating cementing said wire to said tube, a longitudinal band on said winding substantially parallel to said slot being free from said coating.

24. An apparatus for the electrical projection of pictures comprising means for forming an electron current image of the pictured field, a diaphragm arranged in the plane of said electron current image having a linear scanning aperture therein, a thermionic cathode arranged behind said aperture, a plurality of isolated control elements arranged in planes perpendicular to said aperture and substantially surrounding said cathode, an anode screen positioned to accelerate electrons emitted from said cathode to form a secondary electrical image, and means for dissecting said secondary image to form a picture current.

25. An apparatus for the electrical projection of pictures comprising means for forming an electron current image of the pictured field, a diaphragm arranged in the plane of said electron current image having a linear scanning aperture therein of substantially the same length as the pictured field, a thermionic cathode arranged behind said aperture, a plurality of isolated control elements arranged in planes perpendicular to said aperture and substantially surrounding said cathode, an anode screen positioned to accelerate electrons emitted from said cathode to form a secondary electrical image, and means for dissecting said secondary image to form a picture current.

26. An apparatus for the electrical projection of pictures comprising means for forming an electron current image of the pictured field, a diaphragm arranged in the plane of said electron current image having a linear scanning aperture therein, a thermionic cathode arranged behind said aperture, a plurality of isolated control elements arranged in planes perpendicular to said aperture and substantially surrounding said cathode, an anode screen positioned to accelerate electrons emitted from said cathode to form a secondary electrical image, a target positioned to receive said image, and a shield for said target having a scanning aperture therein.

27. An apparatus for the electrical projection of pictures comprising means for forming an electron current image of the pictured field, a diaphragm arranged in the plane of said electron current image having a linear scanning aperture

therein, a thermionic cathode arranged behind said aperture, a plurality of isolated control elements arranged in planes perpendicular to said aperture and substantially surrounding said cathode, an anode screen positioned to accelerate electrons emitted from said cathode to form a secondary electrical image, a target positioned to receive said image, and a shield for said target having a scanning aperture therein arranged perpendicular to the plane of said first mentioned scanning aperture.

28. In an apparatus for the electrical projection of pictures, an envelope, a substantially plane window in said envelope, a photo-sensitive foraminated cathode arranged adjacent said window to receive an optical image therethrough, an anode screen adjacent said cathode and substantially parallel thereto, a diaphragm in said envelope having a substantially linear scanning aperture therein and positioned to receive electrons accelerated from said cathode by said anode, and means arranged behind said aperture for initiating an electron stream varying in spatial distribution in consonance with the electron density admitted from the cathode through the aperture.

29. In an electrical discharge apparatus, a substantially linear cathode, a hollow member of insulating material, a plurality of isolated grid elements wound on said member substantially encircling said cathode, and means for directing an electron stream against said grid elements to control the potentials thereof for determining the distribution of electron flow from said cathode.

30. In a cathode ray tube wherein the beam thereof is moved to produce scansion of a picture area, the method of scansion which comprises developing a cathode ray stream representative of a picture, cyclically moving said stream over an aperture to provide scansion in one dimension only, developing a second cathode ray stream representing the result of said scansion and cyclicallly moving the latter stream along another dimension to scan said latter stream in said second dimension and thus provide a signal proportional to the intensity of illumination of successive elements of said picture area.

31. In a cathode ray tube wherein the beam thereof is moved to produce scansion of a picture area, a method of scansion which comprises developing a cathode ray stream representative of a picture, cyclically moving said stream at one frequency over an aperture to provide scansion in one dimension only, developing a second cathode ray stream representing the result of said scansion and cyclically moving the latter stream at a different frequency along another dimension to scan said latter stream in said second dimension and thus provide a signal proportional to the intensity of illumination of successive elements of said picture area.

32. In a cathode ray tube television system a method of electronic scansion which comprises developing a cathode ray stream representative of a picture, moving said stream along one dimension only of a picture area to produce separate and alined charges representing the scansion of a single picture area dimension, developing a second cathode ray stream, utilizing said charges to vary the intensity of said second stream, and moving said latter stream along another dimension to provide a signal proportional to the intensity of illumination of successive elements of said picture area.

PHILO T. FARNSWORTH.

Nov. 30, 1937. P. T. FARNSWORTH 2,100,842

CHARGE STORAGE TUBE

Filed Sept. 14, 1935

Fig. 1.

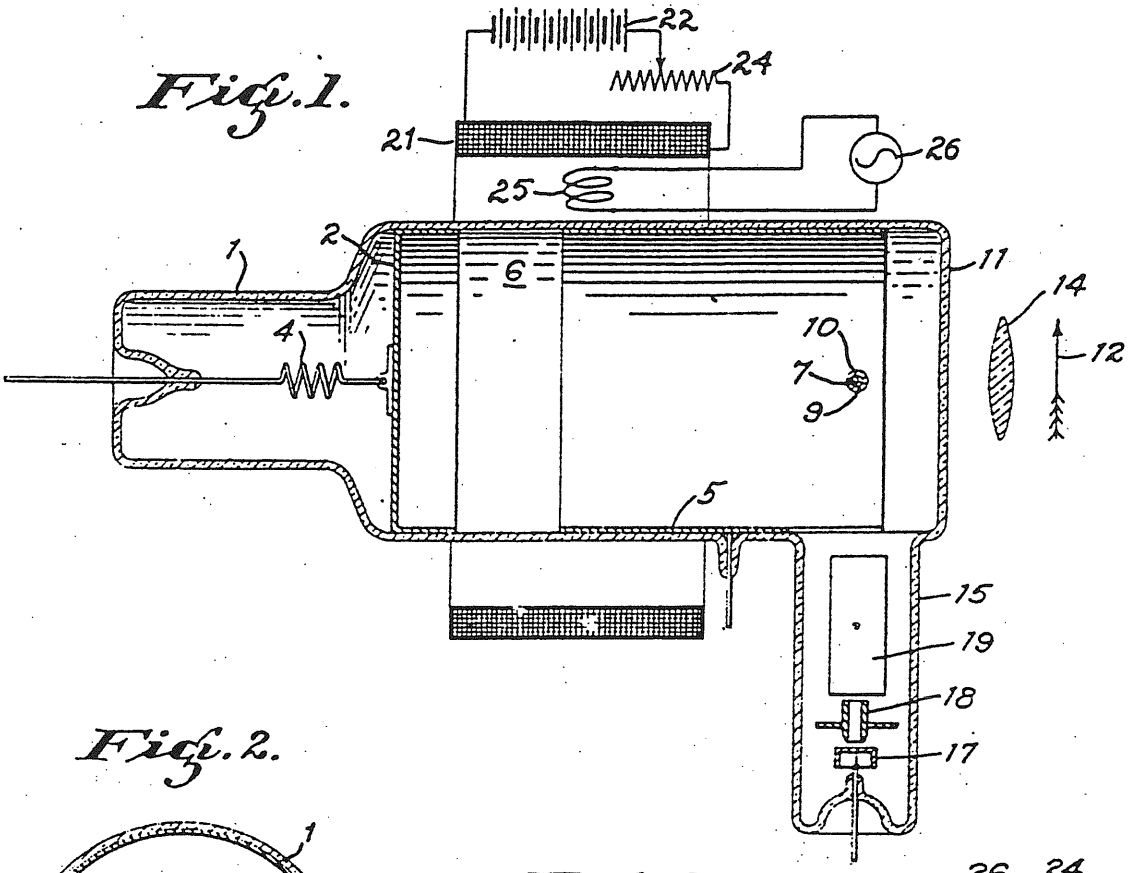


Fig. 2.

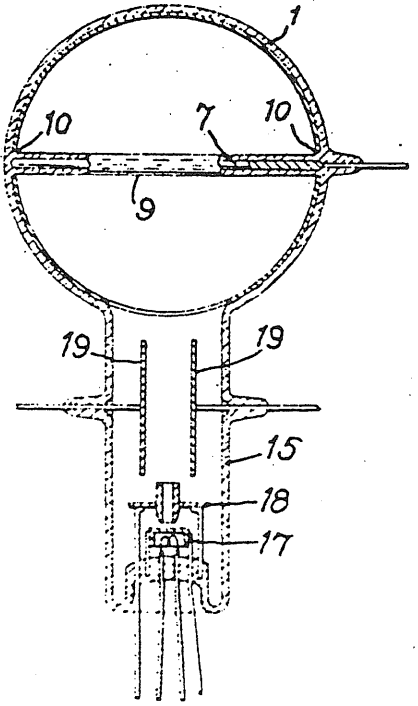
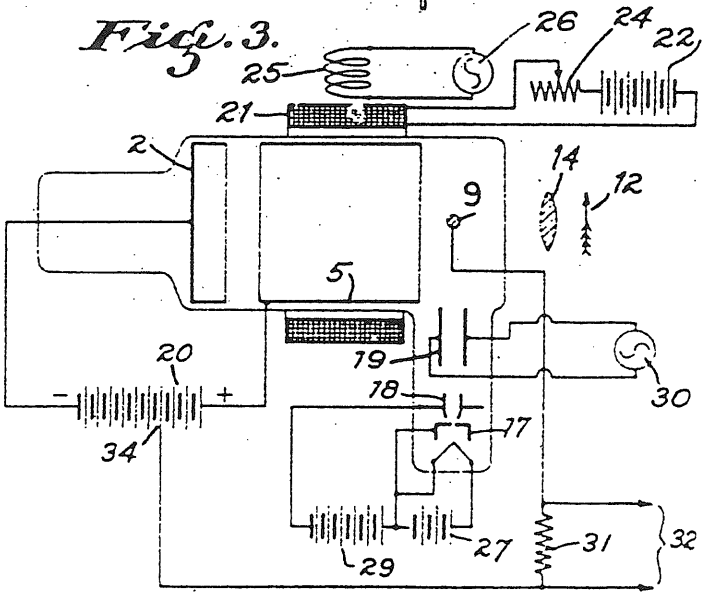


Fig. 3.



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2,100,842

CHARGE STORAGE TUBE

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Application September 14, 1935, Serial No. 40,563

6 Claims. (Cl. 250—27.5)

My invention relates to a cathode ray dissector tube, and more particularly to a tube structure wherein electron beam analysis may be carried out, primarily for the purpose of the production of a train of television signals or for other oscillographic uses.

This application is a companion application to application Serial No. 30,116, filed July 6, 1935, for a Charge storage amplifier, filed contemporaneously with the present case, and I describe and claim herein the tube structure described but not claimed in the above application.

Among the objects of my invention are: To provide a cathode ray tube of high sensitivity for television transmission or general oscillographic use; to provide a cathode ray tube capable, when energized, of use when illuminated by reflected light of ordinary intensity; to provide a dissector tube having an output greater than that obtained from the usual type of photoelectric dissectors; to provide a television dissector tube which will have an output when energized of sufficient power to greatly reduce subsequent amplification; to provide a photoelectric scanning tube having a charge storage electrode therein; to provide a charge storage electrode for use in a cathode ray tube; to provide a photoelectric cell whereby relatively large curents may be obtained in the dissection of an image; to provide an amplifying means which can be applied to an oscillograph tube; to provide an amplifying tube for photoelectric currents whereby extremely high amplifications may be obtained within the tube itself; to provide a means for charging an insulated surface; to provide a cathode ray tube having the full equivalent therein of a photoelectric mosaic without any actual mosaic structure; to provide a means for fixing charges on an insulator; to provide a means of neutralizing these charges; and to provide a simple and efficient cathode ray dissector tube.

Other objects of my invention will be apparent or will be specifically pointed out in the description forming a part of this specification, but I do not limit myself to the embodiment of the invention herein described, as various forms may be adopted within the scope of the claims.

In my previous patents and application for U. S. Letters Patent, as follows: Patent No. 1,773,980, issued Aug. 26, 1930, Patent No. 1,844,949, issued Feb. 16, 1932, and Patent No. 1,941,344, issued Dec. 26, 1933, and Serial No. 668,066, filed Apr. 26, 1933; and others, I have described television transmitting apparatus and [illegible] of the object or picture field is projected upon a photosensitive cathode and the emitted electrons are accelerated and focused to form an electron image. By "electron image" I mean a plane through which the electron stream passes, the electron density of which varies spatially across the stream in the same manner as the illumination intensity varies across the optical image. In other words, the electron density values represent spatially the illumination of the picture field.

The electron stream forming this image may be deflected by means well known in the art, but preferably by magnetic fields, to pass over a stationary aperture in such a manner as to effect a scanning of the image. Selected portions of the electron stream passing through the aperture are collected to form a picture current or train of picture signals which may be amplified and modulated upon a radio wave or, if desired, transmitted by wire or other means.

This method of television transmission offers the advantage of having no moving mechanical parts and of being suitable for the electrical dissection of pictures, having any desired fineness of detail. The principal weakness of this method, however, lies in the fact that only a relatively small portion of the electrons emitted from the total photoelectric area pass through the aperture at any given instant, and at the present time photoelectric emission is relatively small in intrinsic value.

Furthermore, as greater detail is required apertures must be made smaller as there are practical limits to the actual size of the photoelectric emitter. Smaller apertures receive fewer electrons. It is necessary, therefore, in operation of such devices for the highest possible sensitivity to be obtained from the photoelectric surfaces, and even then high gain amplifiers are necessary in order that satisfactory picture currents can be obtained; in fact certain devices of this sort operate with a maximum aperture collection of from zero to twenty electrons for full range operation. With such small output currents, therefore, attempts to amplify the signals above certain limits will bring in background noise, Shottke effect and other factors ordinarily negligible, which tend to make the amplified signals unsatisfactory and distorted. The received picture will therefore be lacking in the detail which it would have if such interference, due to extreme amplification, were not present.

In the present invention the fundamental principles of my previous inventions are retained. An electron image corresponding to the optical im-

age is formed and is dissected as before. I utilize the electron image, however, to produce a charge image which is then scanned by a separate uniform electron beam to neutralize the charges, and thus produce a train of signals.

Describing my present invention in general terms as relates to method, I prefer to form a stream of electrons in space, representing in cross sectional elementary densities the illumination of the corresponding elementary areas of the optical image. This electron stream is then scanned past an insulating surface to form a charge image of one complete line of the electron image thereon, the charge image being preferably formed perpendicular to the direction of deflection.

A stream of electrons is then created having a dimension of elementary extent, and this stream is then passed over the charge image to successively neutralize the charges in the image. The electrons necessary to neutralize the charge at various points along the charge image are then utilized to produce a train of picture signals.

I prefer to form the line charge image at the low frequency rate and to wipe the charges off the insulating material at a high frequency rate.

Broadly, in terms of apparatus, my invention comprises a tube having a fine wire extending across the tube in the path of the electron image, this wire being coated with a thin layer of insulating material, preferably glass. This wire will be a source of the television signal and preferably will be maintained at a voltage of the order of ten volts negative with respect to the anode. The anode will preferably be a ring shaped wall coat adjacent to the window of the tube. The insulated wire is placed so as to be perpendicular to the direction of low frequency scanning.

Perpendicular to the wire an electron gun is positioned to project a low voltage cathode ray of small cross section and of elementary dimension across the wire. This ray is deflected back and forth along the wire to provide the high frequency scanning.

In one method of operation of the present device, the photoelectrons in the electron image are accelerated at sufficient velocity to knock secondary electrons out of the insulating coating on the wire. Thus a line of the electron image will be recorded in the form of positive charges bound upon the surface of the glass coating. These will be neutralized by electrons from the electron gun as the ray therefrom is swept along the length of the wire, and the discharge will produce surges of current in the wire in accordance with the capacities between the charges on the surface of the glass and the wire within. The velocity of the scanning electrons is preferably limited so that they do not cause secondary emission. Therefore they leave the surface uniformly negatively charged and ready for the next line of photoelectron charges.

In another method of operation I employ photoelectron velocities less than those required to produce secondaries, and a higher velocity in the scanning ray electrons. In this manner the photoelectric charges upon the wire are negative and they are neutralized by production of the positive condition of the surface when scanned by the gun. It is obvious, therefore, that the photoelectric charges are stored during the period of one high frequency scanning cycle, thus giving a multiplication on the order of several hundred, the multiplication depending upon whether the positive or negative condition obtains. The method has the advantages of a mosaic without employing an actual mosaic surface, as the charges are bound and dissipated only by leakage. The method is of course adapted to a surface as well as to a wire, as a thin sheet of mica with a metal coating on the side opposite to the photocathode is of course a full equivalent of the wire described.

In the case where a surface is used, it is of course obvious that the scanning beam shall be of elemental dimension in all dimensions; in other words, of elemental cross section, and that both high and low frequency scanning shall be done with this beam.

In its broad aspect therefore, in terms of method, my invention comprises directing a stream of photoelectrons against an insulated surface to produce fixed charges thereon, in accordance with the illumination intensities of an optical image, and utilizing the charges to create a current representing the image. This method is broadly covered in my copending application for an Electron image amplifier, Serial No. 29,242, filed contemporaneously with the present application, the system for practicing the method being somewhat modified herein.

In the following description and discussion the word "photoelectron" is used to designate the emission from a photoelectric surface in accordance with the illumination thereof by an optical image, it being understood that the electron image formed by the photoelectrons is at all times maintained in optical image relation. "Scanning electrons" shall be taken to mean electrons existing in a stream whose cross section has uniform electron densities.

In the drawing which accompanies this application and is made a part hereof:

Figure 1 is a longitudinal section, partly in elevation, of a dissector tube utilizing a line charge image.

Figure 2 is a cross sectional view taken as indicated by the line 2—2 of Figure 1.

Figure 3 is a diagram reduced to lowest terms, showing how the tube of Figure 1 may be connected in operation.

Referring directly to the drawing for a detailed description of the specific embodiments of my invention illustrated therein, and first referring to Figures 1, 2 and 3 which illustrate a charge storage dissector tube wherein the charge is stored a line at a time, an envelope 1 is provided at one end with a photoelectric cathode 2, outside connection being made by connection lead 4 through seal 5.

I prefer in this case to make the cathode of cup shape and deposit on the wall of the tube a ring anode 5, the edges of the anode and cathode approaching but leaving a space 6 therebetween.

Across the end of the tube I prefer to position a horizontal tungsten rod 7 which is provided with a thin glass coating 9, and in order to allow the passage therethrough of this composite electrode I prefer to remove a portion of the anode film 5 to form apertures 10—10 therein where the wire passes through the wall of the tube. The opposite end of the tube is provided with a window 11 through which an optical image of an object 12 may be projected by means of a lens 14 on the cathode 2.

Positioned in the lower end of the tube in a side arm 15 and in the plane of the tungsten rod is an electron gun assembly adapted for supplying a fine line beam intersecting the composite electrode 7—9. This gun comprises an indirectly

heated cathode 17 and a perforated anode 18, the perforation being positioned so that the beam issuing therefrom intersects the composite electrode and is perpendicular thereto. The side arm 15 is also provided with a pair of horizontal electrostatic deflecting plates 19 which, when energized, will cause the electron beam issuing from the electron gun to traverse the extent of the composite electrode.

The operation of the device is in accordance with two methods, but as the apparatus for creating the operation is similar, the diagrammatic hookup shown in Figure 3 will serve to illustrate both methods.

Here, the cathode 2 is connected to the anode 5 through an anode battery 20 so that the anode is positive to the photoelectric cathode. When the optical image from object 12 is focused by means of lens 14 onto the photoelectric cathode tube, it emits electrons at every elementary area thereof in proportion to the illumination these areas receive, and these electrons are drawn outwardly in space under the influence of the anode potential. The electrons emitted from the photoelectric cathode are maintained in the electron image relation by means of a focusing coil 21 whose field is produced by current from a source 22 under the control of a rheostat 24 so that the electrons focus in the plane of the storage electrode 7—9, and the electron image is scanned across the storage electrode in a direction perpendicular thereto by means of a field of a low frequency magnetic deflecting coil 25 supplied by a low frequency oscillator 26. At the same time the electron gun is energized, the cathode 17 by means of cathode battery 27, and the anode thereof by means of anode source 29, to project a beam of scanning electrons upon the insulating surface of the tungsten rod 7, and this scanning beam is deflected along the storage rod by means of charges placed upon the horizontal deflecting plates 19 from a high frequency oscillator 30. The tungsten rod is connected through an output resistor 31 having output leads 32 thereacross to a point 34 intermediate the positive and negative end of the anode battery 20.

In one method of operation the photoelectrons are accelerated by means of the anode potential from source 20 to a sufficient velocity to knock secondary electrons out of coating 9 as the image is scanned thereacross. These secondary electrons are of course picked up by the anode 5, leaving charges which will represent a line of the electron image recorded in the form of positive charges bound upon the surface of the glass coating. After these charges have been formed the electrons from the electron gun assembly comprised in the beam projected thereby, sweep across the length of the wire and discharge the positive charges on the wire. This discharge of the charges upon the wire in sequence as the beam sweeps across will produce in the tungsten rod 7 surges of current in accordance with the capacity between the surface charges and the rod beneath, these currents passing through output resistor 31 and appearing as potential changes in output leads 32. The potential placed upon anode 18 of the electron gun is made such that the velocity of the scanning electrons is less than that required to produce secondary emission from the insulating surface upon impact therewith. The surface therefore, after scansion by the electron beam, will be left negatively charged and thus ready for the next line of photoelectron charges

The other method of operation is to reduce the potential on anode 5 to a point where secondaries are not produced. The charges produced on insulating surface 9 by the photoelectrons will therefore be negative charges and will be bound thereon, and I then prefer to raise the voltage on the electron gun 18 to a point where these electrons will cause secondary emission from the surface 9 which will then discharge the charges on the surface in the opposite direction and will leave the surface positively charged, ready for the next negative charge to be supplied by the photoemission.

It is obvious from the above description that the photoelectric charges will be stored during the period of one scanning cycle of the scanning beam, thus giving a considerable multiplication, the multiplication being substantially equal in both cases inasmuch as the charges are stored and bound upon the insulating surface. It is obvious that the charge pattern, in case a line storage is used, will have a value which is determined by the period of the high frequency scanning.

It is obviously within the scope of this application and the claims appended hereto, to make the charge storage surface rectangular and of an area comparable to the whole of the electron image, and then scan the charge image with an electron beam moving in two directions. In this latter case the charge will be stored during the entire low frequency scanning cycle. In this latter instance I prefer to utilize a thin sheet of mica backed with a metal film for the charge storage of electrode, the full functional equivalent of a photoelectric mosaic being produced, thus avoiding the difficulties entering into satisfactory mosaic production.

I claim:

1. A thermionic tube comprising an envelope containing a photoelectric cathode having a surface of picture area capable of emitting electrons when illuminated, a single linear electrode having a complete covering of insulating material and extending across one major dimension of said surface and spaced therefrom, a cathode and anode cooperating to produce an electron beam defined to an elemental dimension in the direction of extent of said linear electrode, and a pair of deflection plates positioned to deflect said beam along said linear electrode when energized.

2. A thermionic tube comprising an envelope containing a photoelectric cathode having a surface of picture area capable of emitting electrons when illuminated, a single wire having a complete covering of insulating material and extending across one major dimension of said surface and spaced therefrom, a cathode and anode cooperating to produce an electron beam defined to an elemental dimension in the direction of extent of said linear electrode, and a pair of deflection plates positioned to deflect said beam along said linear electrode when energized.

3. A thermionic tube comprising an envelope containing a photoelectric cathode having a surface of picture area capable of emitting electrons when illuminated, a single wire supported by the side walls of said envelope, completely covered by an insulating material and extending across one major dimension of said surface and spaced therefrom, a cathode and anode cooperating to produce an electron beam defined to an elemental dimension in the direction of extent of said linear electrode, and a pair of deflection plates posi-

tioned to deflect said beam along said linear electrode when energized.

4. A thermionic tube comprising an envelope containing a photoelectric cathode having a surface of picture area capable of emitting electrons when illuminated, a single wire supported by the side walls of said envelope, completely covered by an insulating material and extending across one major dimension of said surface and spaced therefrom, said wire having a connection extending through said envelope, a cathode and anode cooperating to produce an electron beam defined to an elemental dimension in the direction of extent of said linear electrode, and a pair of deflection plates positioned to deflect said beam along said linear electrode when energized.

5. A thermionic tube comprising an envelope containing a photoelectric cathode having a surface of picture area capable of emitting electrons when illuminated, a single conductor having a complete covering of insulating material and extending across at least one major dimension of said surface and spaced therefrom, a cathode and anode cooperating to produce an electron beam defined to an elemental dimension in the direction of extent of said linear electrode, and a pair of deflection plates positioned to deflect said beam along said linear electrode when energized.

6. A thermionic tube comprising an envelope containing a photoelectric cathode having a surface of picture area capable of emitting electrons when illuminated, a single conductor having a complete covering of magnesium oxide and extending across at least one major dimension of said surface and spaced therefrom, a cathode and anode cooperating to produce an electron beam defined to an elemental dimension in the direction of extent of said linear electrode, and a pair of deflection plates positioned to deflect said beam along said linear electrode when energized.

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May 24, 1938. P. T. FARNSWORTH 2,118,186

IMAGE RECEIVING TUBE

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Fig. 1.

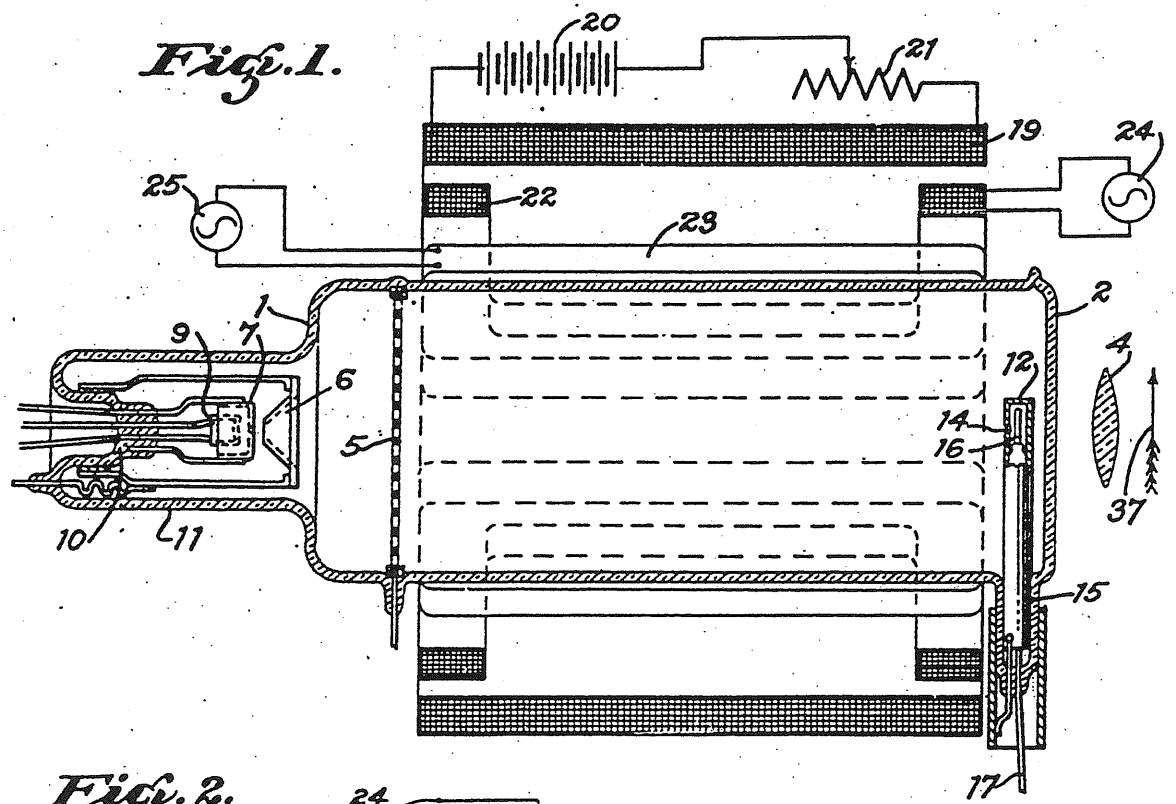

Fig. 2.

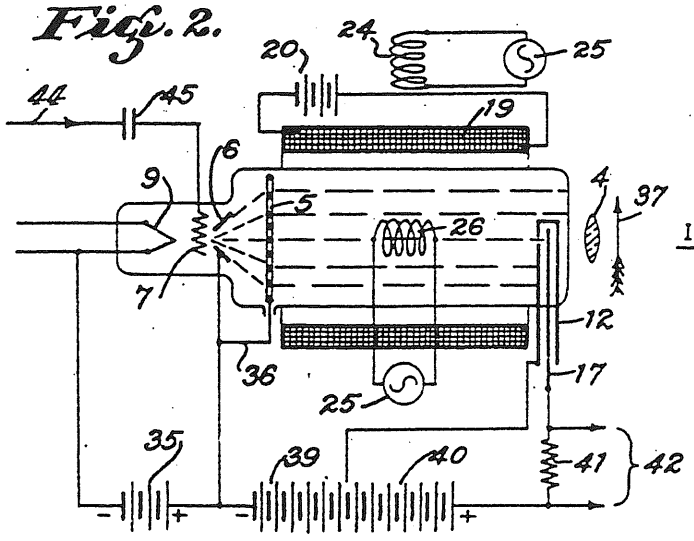

Fig. 3.

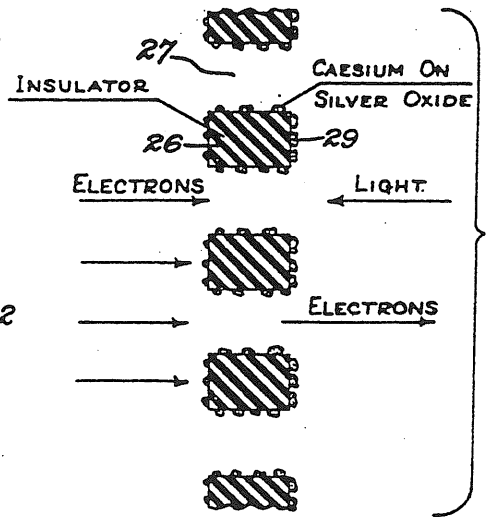

Fig. 4.

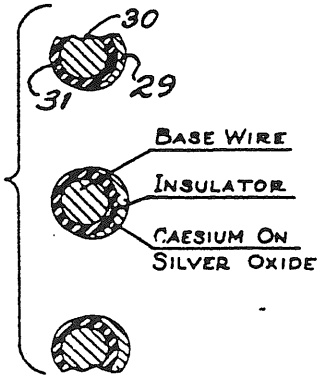

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IMAGE RECEIVING TUBE

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Fig. 5.

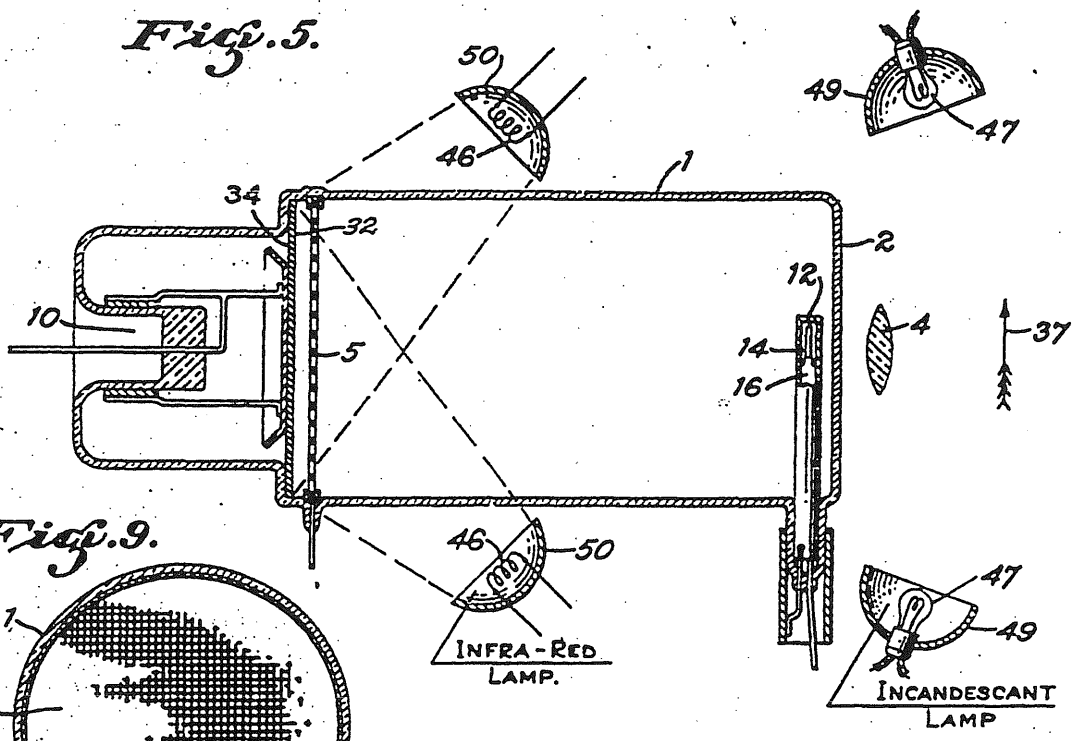


Fig. 9.

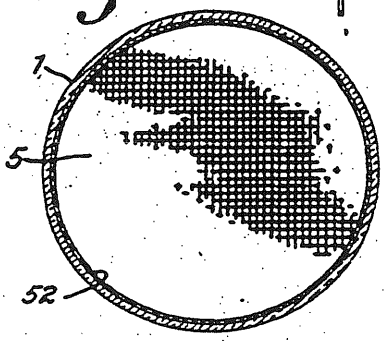


Fig. 8.

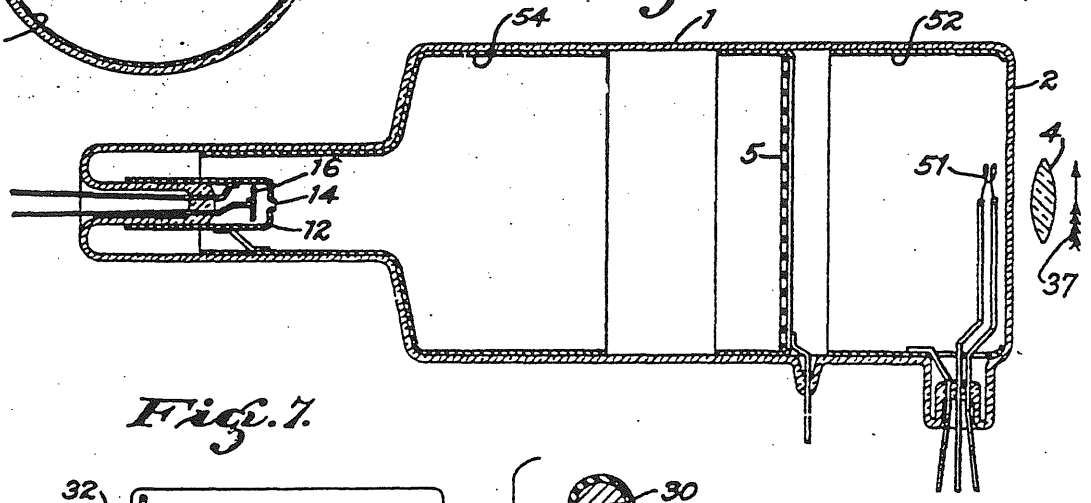
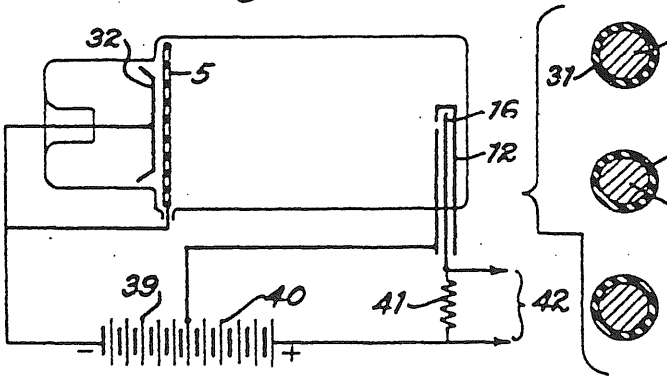


Fig. 7.



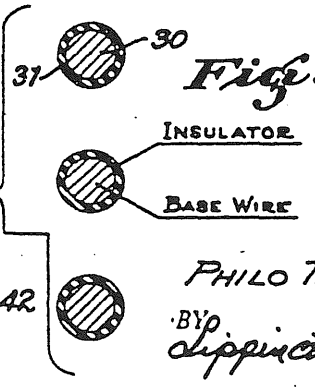


Fig. 6.

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Fig. 10.

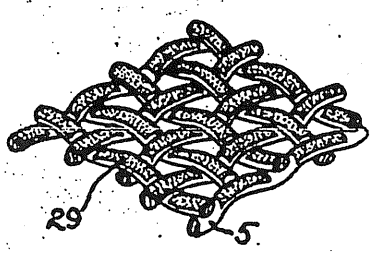


Fig. 11.

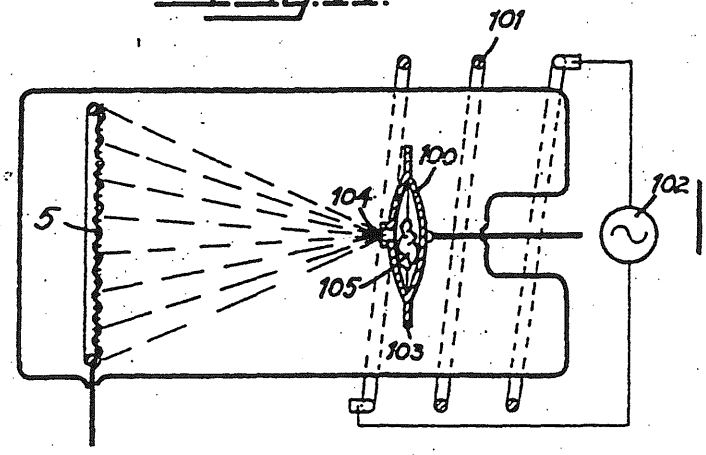


Fig. 12.

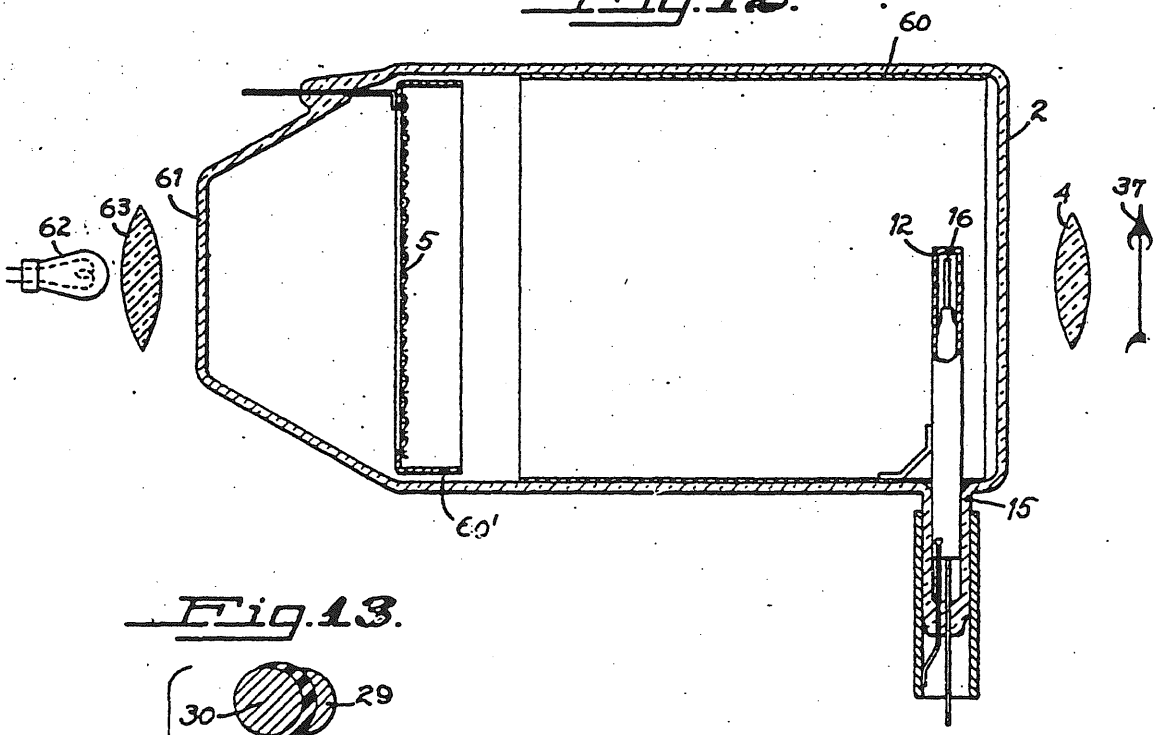
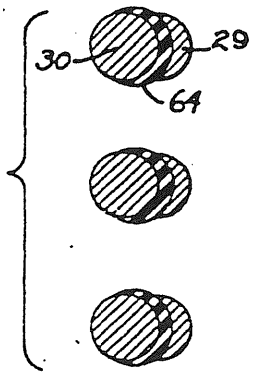


Fig. 13.



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UNITED STATES PATENT OFFICE

2,118,186

IMAGE RECEIVING TUBE

Philo T. Farnsworth, San Francisco, Calif., assignor to Farnsworth Television Incorporated, San Francisco, Calif., a corporation of California

Application July 15, 1935, Serial No. 31,410

4 Claims. (Cl. 250—27.5)

My invention relates to a thermionic device, and more particularly to a cathode ray tube adapted to produce an electron image of greater intensity than can be ordinarily produced directly by the impact of an optical image upon a photoelectric surface.

The present application is a continuation in part of my invention disclosed and claimed as to system and method in my application, Serial No. 29,242 filed July 1, 1935 for an Electron image amplifier, this application dealing solely with tube structure.

Among the objects of my invention are: To provide a photoelectric tube having a high output; to provide a photoelectric tube which when energized will produce an output current greater than can be produced by the impact of light upon the photoelectric surface alone; to provide an image amplifying tube having an effective photoelectric emitter of greater sensitivity than has hitherto been produced; and to provide a simple and efficient electron image amplifying tube particularly suitable for use in television systems for the creation of a train of television signals.

Other objects of my invention will be apparent or will be specifically pointed out in the description forming a part of this specification, but I do not limit myself to the embodiment of the invention herein described, as various forms may be adopted within the scope of the claims.

In my prior application above referred to, I have described and claimed an embodiment of a method of electron image amplification employing the tube of the instant application. In previous applications and patents of mine I have described television transmitting apparatus and systems wherein an optical image of the object or picture field is thrown upon a photosensitive cathode and the emitted electrons are accelerated and focused to form an electron image. By electron image I mean a plane through which the electron stream passes, the electron density of which varies spatially across the stream in the same manner as the illumination density varies across the optical image. In other words, the electron density values represent spatially, the illumination of the picture field.

The electron stream forming this image may be deflected by means well known in the art, but preferably by magnetic means to pass over an aperture in such a manner as to effect the scanning of the image. Selected portions of the electron stream passing through the aperture are collected to form a picture current or train of picture signals which may be amplified and modulated upon a radio wave, or transmitted by wire. This method of television transmission offers the advantage of having no moving parts and of being suitable for the electrical projection of pictures having any desired fineness of detail.

The principal weakness of this method lies in the fact that only a relatively small portion of the electrons emitted from the total photoelectric area is used at any given instant and at the present time photoelectric emission is relatively small in intrinsic value. Therefore, the highest possible sensitivity must be obtained from the photoelectric surfaces and even then high gain amplifiers are necessary in order that satisfactory picture currents can be obtained. With small output currents, attempts to amplify the signals above a certain level bring in background noise, Shottke effect and other ordinarily negligible factors which tend to make the amplified picture currents unsatisfactory and distorted, and the received picture lacking in the detail which it would have if such interference were not present.

The tube of the present invention enables the fundamental principle of my previous inventions to be retained while other desirable features are added. An electron image corresponding to the optical image is formed and is thereafter dissected as before. In the present tube, however, the image has a considerably higher average value than the previous device because of the fact that a space charge is formed, the electrons in the space charge being released by the action of the light in the optical image. I am therefore able to produce electron images with the present device which are far more powerful than the electron images which are heretofore produced. Under these circumstances, when the picture is scanned, picture currents of much greater amplitude are obtained in the tube output thereby eliminating high gain amplifiers with their objectionable features.

Describing my invention in broad terms, I prefer to utilize an envelope containing a source of electrons, these electrons being preferably low velocity electrons. In certain cases, I may use a thermionic emitter for this source but in other cases, I prefer to utilize a photoelectric surface and flood the surface with long wavelength light in order to obtain a stream of low velocity electrons therefrom. I then position in the path of this stream an apertured electrode or grid capable of having a charge fixed thereon in accordance with the spatial distribution of illumination intensities existing in an optical image.

At the other end of the tube, I prefer to position an apertured electrode, the aperture being of elemental area and positioned to allow electrons to pass therethrough and I place, immediately behind the aperture, a collecting anode to intercept electrons passing through the aperture. The tube when energized is supplied with moving magnetic fields which scan the electron image past the aperture so that successive elementary areas thereof may be collected to produce a train of television signals.

Various other modifications and applications of my invention will be apparent to those skilled in the art and for other broad aspects of my invention I prefer to refer to a detailed description of several preferred embodiments of my invention as shown in the drawings, of which

Figure 1 is a longitudinal sectional view of a television dissector tube provided with focusing and scanning coils, together with means for projecting an optical image therein.

Figure 2 is a diagrammatic circuit reduced to lowest terms showing how the device of Figure 1 may be operated to produce a train of television signals.

Figure 3 is a detailed sectional view of one form of grid.

Figure 4 is a detailed view in section of another form of grid.

Figure 5 is a cross sectional view of another form of dissector tube showing differential illumination of the photosensitive surface therein.

Figure 6 is a cross sectional view of a portion of the control grid of the tube showing in Figure 5.

Figure 7 is a diagrammatic circuit showing how the tube of Figure 5 may be operated.

Figure 8 is a longitudinal sectional view of another embodiment of my invention.

Figure 9 is a cross sectional view which is identical with cross sectional views of the device shown in Figures 1, 5 and 8, looking toward the charge storage electrode.

Figure 10 is a perspective view of a mesh mosaic.

Figure 11 is a diagrammatic view of apparatus used in forming a silver mosaic.

Figure 12 is a longitudinal sectional view of another modification of my invention.

Figure 13 is a cross sectional view of a composite grid having two photoelectric surfaces.

Describing the apparatus in detail, without reference to the operation thereof, which will be taken up later, and referring directly to the modification shown in Figure 1, an envelope 1 is provided at one end and with a transparent window 2 in front of which is placed an optical system 4 in such a manner as to focus an optical image of an object upon a charge storage electrode or grid 5 positioned adjacent the opposite end of the tube. On the other side of this grid there is positioned a wide angle electron gun comprising a cone-shaped apertured anode 6, a control grid 7, and preferably an indirectly heated cathode 9. This assembly is preferably mounted on a stem 10 in an extension arm 11 of the envelope.

Adjacent the window end of the tube an apertured anode assembly is provided comprising a finger tube 12 having an aperture 14 facing the grid 5 mounted securely in an anode extension 15 of the envelope. Mounted inside of the finger 12 is a collecting plate 16, positioned immediately back of the aperture 14, mounted on a lead 17.

The tube is preferably provided with a focusing coil 18 energized by a focusing source 20 under the control of a variable resistor 21 which provides a longitudinal magnetic field between the grid 5 and the scanning aperture 14 for the purpose of maintaining the electron image in proper spatial relationship during its passage therebetween.

The tube is also provided with exterior coils 22 and 23 positioned substantially at right angles to each other for moving the electron image in two directions over the scanned aperture 14, the magnetic fields of these coils being formed by energization by scanning oscillators 25 and 24 respectively.

Several different types of grid structures may be used with this device, but in any case the grid member 5 is apertured preferably with an area devoted to the apertures equal to that of the supporting material. For example, I may make, in certain cases, my grid entirely of insulating material as shown in Figure 3. Here the insulator 26 is provided with apertures 27 and is also provided with a layer of caesium on silver oxide 29. This layer is formed in the usual manner for forming photoelectric surfaces, the silver being deposited thereon in such a manner that it congeals in droplets so that a mosaic is formed with the caesium deposited thereon, leaving photoelectric islands more or less uniformly insulated one from the other, as is well known in the art.

Another form of grid is shown in Figure 4 where the base material 30 is a conducting material such as nickel wire, for example, which has deposited thereon a layer of insulating material 31 and over the insulating material the mosaic 29 of caesium on silver oxide is formed, as described before. The preferred way of forming the grid of this latter construction is to utilize a mesh screen of nickel, for example, having rather larger spaces between the grid wires than the area of the wires themselves and smoking the entire screen with burning magnesium until the wires are covered with magnesium oxide to a point where the spaces are approximately equal to the area of the composite member. Caesium on silver oxide is then formed upon the magnesium base to form the mosaic, as will be later described.

When I desire to form a mosaic on an insulating surface of a mesh grid fabric, I have found that it is not necessary to follow the complicated and uncertain process above referred to.

In Figure 11 I have shown a preferred apparatus for forming a mosaic on the mesh grid. The grid is covered with insulating material, at least on the side facing the optical image, preferably by smoking with magnesium oxide as above described, and silver is evaporated thereon preferably from substantially a point source 100, a convenient means being the application of eddy currents from a coil 101 energized by an oscillator 102 to a container 103 having an aperture 104 facing the grid and enclosing silver metal 105. The silver, being evaporated in vacuo, travels in straight lines and therefore casts sharp shadows. As the individual wires in the mesh alternately pass over and under the wires at right angles to them, the silver deposit is separated into small rectangles the size of the mesh. No silver is deposited under the overhang of the wires, and not only do I obtain substantially perfect insulation between the silver islands, but I am able to accurately control the size of the islands by changing the mesh of the fabric. A mosaic of this type is shown in Figure 10 in perspective and in Figure 13 in cross section.

In practice, a completely opaque film of silver has been evaporated onto a grid member, and the resistance between two contacts $\frac{1}{16}$ of an inch apart on such a screen measured to be in excess of 10^{14} ohms, showing the extremely good insulation between islands. I prefer, however, to utilize only a fairly thin film of silver, and then when the tube is formed this film is completely oxidized, utilizing, as is customary, a radio frequency discharge in pure oxygen.

I also prefer to completely clean up the excess caesium after the tube is formed. There are a number of ways of accomplishing such a clean-up but I prefer to include within the tube, either connected to the cathode or the anode, a fairly large surface of pure silver which may be oxidized with a fairly heavy coating. After the tube is formed, therefore, this surface is capable of absorbing a large amount of caesium, even after the thin film of silver on the grid has taken up its maximum.

The preferred procedure, therefore, after the surfaces it is desired to sensitize have reached maximum sensitivity, is to lower the temperature somewhat and bake the tube out in this lower temperature for a sufficiently long time until the excess of caesium within the tube is all taken up by the accessory oxidized silver surface.

Another modification of my invention is shown in Figure 5 and in this case a photoelectric emitter has been substituted for the electron gun, the photoelectric emitter in this case comprising preferably a continuous photoelectric surface 32 formed on a base member 34, preferably a silver plate. This plate is supported on the stem 10 in any customary manner. The grid 5 is then positioned immediately in front of and parallel to the photoelectric surface, and in this case the grid 5 comprises preferably a conductor having an insulating surface. While the entire grid structure may be an insulator, I prefer to utilize the conducting base 30 provided with a relatively thin layer of magnesium oxide formed thereon as above described, and in this case I do not place upon the insulator any photoelectric material.

Referring directly to the modification shown in Figure 1 connected as in Figure 2 and assuming that it has a grid as shown in Figure 3; in other words, a grid which is completely an insulator, the anode 6 of the electron gun is connected to the cathode in series with an anode battery 35 and the cathode 9 is energized in the usual manner so that the entire grid structure 5 will be bombarded with a suitable amount of 100 to 300 volt electrons. The grid will then assume a negative charge just sufficient to prevent these electrons from striking it, thus forming a space charge immediately back of the grid. The potential of the grid, that is, the normal uniform potential of the grid, will be largely determined by a small number of electrons having the highest velocity and due to leakage in the grid structure, the entire grid will assume a uniform charge equilibrium.

Inasmuch as the grid in this instance is entirely formed of insulating material, the uniform grid charge in the structure shown in Figure 3 will be slightly higher than in the structure shown in Figure 4, where the insulating layer is formed on a base wire 30, as I prefer to connect this base wire to the anode 6 by a connection 36. In this case, the negative charge, because of greater leakage opportunity will be slightly less than when the entire grid is formed of insulating material.

After the grid has assumed a uniform negative charge and the space charge has been formed behind the grid due to this negative charge, an optical image of an object 37 is focused by means of optical system 4 on the side of grid 5 opposite to that being bombarded. This optical image falls on the mosaic photoelectric layer 29 and causes emission therefrom, the electrons being drawn toward anode 12, those of some particular elementary area entering aperture 14 and being collected on collecting plate 16. In order to create electron traversal of the tube, anode 12 is maintained at a positive potential by means of an anode battery 39 and the collecting plate 16 is maintained at a potential positive to anode 12 by collecting source 40. The difference between the number of electrons collected by the collecting plate 16 and finger 12 passing through output resistor 41 creates a potential available for further use in output leads 42.

When electrons are emitted from the mosaic surface due to the action of the image light, they will of course be emitted in proportion to the intensity of the light falling on the individual mosaic islands and the islands will become more or less positive due to the loss of electrons in accordance with the light striking them. This results in lowering the negative potential of different portions of the grid to a new point of equilibrium and results in the formation of a charge image on the grid representing in intensity the light intensity of the image. Electrons from the space charge developed back of the grid 5 are thus able to be drawn through the grid toward the anode 12 and due to the fact that the number drawn through at any particular elemental area is controlled by the charges on elemental areas of the grid, there will be formed in space between the grid and the anode, an electron image. This electron image is maintained in spatial relationship by the focusing coil 19 and is scanned across aperture 14 by the moving magnetic fields developed by the scanning coils and generators positioned as previously described.

If desired, the output of the electron gun can be modulated at radio frequencies by means of the gun grid 7 supplied with a radio frequency modulation voltage through input lead 44 and blocking condenser 45. This allows output amplification with this type of amplifier and in this manner the D. C. component can be preserved and a single side band generated if desired, as will be apparent to those skilled in the art.

I have thus produced by a storage of electrons in a space charge, an electron image of greatly increased intensity over one which could be produced by means of light falling directly upon a photoelectric surface, the emission from this surface being scanned as in my previous inventions. The greatly increased output which appears across output resistor 41 may be amplified with far less amplification and with consequent quietness and freedom from interference and distortion.

Another apparatus for producing electron storage for the purpose of providing an amplified electron image is shown in Figure 5 and connected as shown in Figure 8. In this case, I do not use an electron gun for the source of electrons forming a uniform electron stream, but I prefer to use a flat photoelectric cathode 32.

This cathode is preferably formed as is customary in the art on a silver plate 34 by oxidation and the deposition of caesium until maximum sensitivity to light is obtained and is preferably not a mosaic. The cathode is then flooded with infra-red and red light from lamps 46 until the cathode develops in a specific instance for example, 100 microamperes current. Grid 5 in this case is not photoelectric, but is preferably composed of a base wire 30 of nickel having an insulating coating thereon preferably of magnesium oxide formed as above described.

In operation, the object 37 is illuminated solely by sunlight, for example, or by incandescent or arc lamps 47, care being taken that none of the white light reaches cathode 32 except that which is reflected from the object 37 and focused on the cathode 32 by lens 4. This is accomplished in practice by the use of reflectors 49 on the white lights and as it is also desirable that no red light illuminate object 37 reflectors 50 are used on the red lights, these reflectors being so placed that the light is directed in one case on the cathode alone and in the other case on the object alone. The tube of Figure 5 may be hooked up as shown in Figure 7, the scanning and focusing coils being omitted from the sketch in the interests of simplicity, it being understood that they are to be used in the operation of the device.

Cathode 32 is connected with anode finger 12 in series with the anode source 39. The usual collecting source 40 is connected to the collecting plate 16, the output appearing across output resistor 41 in output leads 42 exactly as in the previous instance. Thus, there will fall upon the cathode surface 32 two different illuminations. One, a low wavelength uniform illumination from the red lamps 46 which causes a uniform emission of low velocity electrons from the cathode. The other illumination is an optical image of light having a wavelength range containing short wavelengths which will produce electrons from cathode 32 falling into a different velocity category and having higher average velocities.

Thus there will be emitted from cathode 32 electrons falling into two velocity categories. One category, made up of a uniform component of low velocity electrons, the other category, a non-uniform electron image of higher velocity electrons. The grid, assuming that no optical image is thrown upon the cathode, will assume a negative charge because electrons reaching the grid collect upon the insulating layer and leak off to the base wire, thus reaching an equilibrium value at perhaps in the neighborhood of three-quarters of a volt. This will form a space charge back of the grid.

When this equilibrium is reached, that is, the equilibrium due to the bombardment by low velocity electrons, the charge on the grid will be uniform throughout. When, however, the optical image reaches the cathode surface, electrons of higher velocity are emitted, which, due to their higher velocity can reach the grid and thus charge the grid more negatively at those points where they do reach it and by an amount in proportion to the numbers reaching it. Inasmuch as the number of high velocity electrons reaching the grid at any elementary area thereof will be dependent upon the illumination of the cathode on corresponding elementary areas thereof by the optical image, it can be seen that a charge pattern is built up upon the grid, this charge pattern modulating the electrons passing through the grid due to the pull of the anode 12, thus forming in the space between the grid and the anode a new electron image of higher intensity which then may be maintained throughout the traversal of the tube in spatial relationship by means of the usual focusing coil and moved across the aperture 14 by the scanning coils to produce a television picture current of greater intensity. In this instance, the grid becomes more negative due to the action of the optical image emission, and modulation is downward.

I have found that by the building up of a space charge behind the grid and then forming a charge pattern on the grid in accordance with an optical image pattern, that I have increased the overall sensitivity of the dissector tube over one thousand times, thus decreasing enormously the amount of amplification necessary in the circuits utilized to handle and make useful the signal train produced by scansion.

In the embodiment shown in Figure 8, the source of the uniform electron stream is a filament 51 and the filament is surrounded by a cylindrical electrode 52 which tends to form a uni-potential space around the cathode emitter so that the electrons will be uniformly accelerated toward the grid 5, in this case provided with a photoelectric mosaic and formed as shown in Figures 3 and 4 or other charge storage electrodes such as are described and claimed in a companion application, Serial No. 30,118, filed July 6, 1935 for a Charge storage dissector.

In Figure 8, the end wall 2 is left free from any film so that the optical image is projected through onto the charge storage electrode 5, the filament assembly being so small that no appreciable amount of light is intercepted thereby. Electrons from the filament charge the mosaic surface 29 a uniform potential and the emission of electrons from the mosaic surface due to the light from the optical image falling thereon causes the formation of a charge image. This charge image modulates the electrons from the filament which are being drawn through the apertures in the charge storage electrode 5, and the modulated stream is then accelerated toward the anode aperture 14 selected areas thereof passing through to be collected by the collecting plate 16.

The space between the charge storage electrode or grid 5 and the collecting anode is partially surrounded by a film 54 on the inside of the envelope which acts as an electrostatic focusing aid and which is usually maintained at the potential of the anode. It will be seen that the structure involved in this particular embodiment is almost identical with that shown in Figures 1 and 5 with the exception that all the electrons travel in the same direction instead of reversing their directions as in the other embodiments.

In all of the specific apparatus embodiments employing my method herein described, a new charge pattern is developed on the control member with each new shift of the light pattern and the action of the tube is independent entirely of scansion. If a shift of the light pattern due to a movement of the object occurs during scansion, the picture produced toward the end of the scanning cycle is simply an intermediate picture between that which was shown at the beginning of the scanning cycle and that which is to come on the following scanning cycle. Even when objects move with the highest speeds customarily occurring within the perception of the human eye there is plenty of time for the charge pattern

to develop as such movements are relatively slow and the period required for the development of the charge pattern exceedingly short. Thus, the readjustment of the charge pattern to motion is always effective before scansion and if motion should occur exactly at the instant of scansion, the charge on the elementary area would be that of the previous intensity before motion occurred as it would be obviously unusual for any fortuitous combination of motions to take place in synchronism with the scanning motion for any perceptible length of time.

My invention also includes the formation of a composite cathode utilizing the same method. In other words, the grid and the cathode are combined so that the same action occurs. Theoretically, if a fine insulating powder is deposited directly on the cathode in such a manner that there are spaces between the powder units, charges would be formed on the insulating upper portions of the powder which would be able to modulate low velocity electrons due to the long wavelength illumination. It would, however, be rather difficult in practice to form the cathode surface under these circumstances and the insulating powder would be likely to become contaminated with caesium and perhaps become conductive. I have, however, been able to produce a composite cathode by using an extremely thin coating of insulating powder, and oxidizing the composite surface by means of a glow discharge in argon after formation of the caesium surface, to clean up all conductive metal overlying the insulating material. When such a composite cathode is formed, I prefer to utilize a small amount of radio frequency excitation applied to the cathode in operation in order to increase the number of electrons striking the insulator.

Another method by which a composite cathode may be made is the formation of the cathode utilizing caesium monoxide as an insulator thereon. When a silver plate having a monoxide layer is processed to form the photoelectric surface, the caesium distilled thereagainst will combine with the caesium monoxide to form caesium trioxide, which is also a good insulator.

Thus, in both cases, a photoelectric surface will be formed having a plurality of insulating islands thereon spaced to allow electron emission therebetween, charges from the emission being formed on the insulating islands and controlling the flow as has been described for the grid in previous paragraphs.

Still another modification capable of practice in my invention is shown in Figure 12. Here, the photoelectric cathode 32 and the grid 5 are combined into a single unit all formed on the grid screen 5. This member is shown in cross section in Figure 13.

In the embodiment shown in Figure 12 the collecting finger assembly 12—16 is mounted in one end of the tube and surrounded with a nickel film 60 preferably connected to finger 12, and the grid screen 5 is mounted facing the opening in the finger 12. In this case I have also provided the envelope with a second transparent window 61 for directing onto the side of the screen 5 opposite the finger the flooding light from a source 62 through a flood lens system 63.

The grid 5 in this instance is formed as shown in Figure 11. The foundation or base wire 30 is smoked so that the insulating material, such as magnesium oxide 64 for example, is deposited only on one side of the grid, and in this instance I prefer to make the foundation material of pure silver wire. The insulating material is then exposed to silver evaporation as before described, so that a mosaic is formed upon the insulating surface. The silver surface is then sensitized as previously described, and at the same time the exposed silver surface of the grid wires on the other side of the grid will also be sensitized. Thus there will be on the grid two completely separate photoelectric surfaces; one facing the flooding light source 62 being connected together to form a continuously conductice surface, and the other, facing the anode finger 12, a photoelectric mosaic surface.

In this particular embodiment I also prefer to provide the grid 5 with a cylindrical wall extension 60', the edges of which extend toward but do not meet film 60. The combination of film and extension constitute an electrostatic lens, as described and claimed in my prior application, Serial No. 56,976, filed December 31, 1935, which helps to maintain the edges of the electron image in sharp focus. In many cases it may be desirable to apply the same type of focusing to the other embodiments described in this application in addition to the focusing means shown.

When the continuously conductive surface is illuminated, the light, which in this case need not be of any different spectral characteristics from that in the optical image, causes electrons to be emitted on the back side of the grid, uniformly all over the entire surface, thus forming an electron source, the emission therefrom creating a space charge on the back of the grid. On the front side of the grid, however, the side where the photoelectric surface is illuminated with light from the object, a charge image representing the optical image projected onto this surface is formed on the mosaic which modulates electrons being emitted from the rear surface and drawn through the grid by the voltage on the finger 12. The electrons passing through the grid form in space, between the grid and the collecting assembly, an optical image which may be scanned in the usual manner.

This particular type of tube is practical to build and is desirable for a number of reasons. The amplification is high and the uniformity of the rear discharge is such that all portions of the mosaic control practically the same number of electrons. It is not necessary to use infrared light on the rear surface as the photoelectric surfaces are separated, and the light from the two sources fall only on their own proper surfaces. Furthermore, one of the principal advantages of this type of tube is that the mosaic elements draw very little current, because of their location on the opposite side of the grid from the source of the flooding electrons.

The response period of this tube may be regulated in several ways. Pure magnesium oxide has such a long leakage time that it is desirable to reduce it either by adding to the magnesium oxide other materials giving less perfect insulation or, as is quite practical to do, to leave a very small residual amount of gas in the tube, the amount of gas left, of course, controlling the discharge time of the mosaic elements. The leakage time may be reduced to the proper point by the controlling amount of residual gas, which has been found too small to affect the electron image in any way or to blur or distort the final television signal when of the proper amount to control the leakage within the limits of the picture frequency.

It should be pointed out that in every embodi-

ment shown a charge image representing the optical image is formed, and this charge image is then used to modulate a uniform stream of electrons, the resultant stream being dissected to form a train of television signals.

I have shown modifications where the charge image is formed on a photoelectric mosaic, and on a surface of insulating material, this surface either having a conductive base, or not, as desired. I have shown that the source of the uniform electron stream may be either a thermionic or a photoelectric source, and I have described a composite grid structure where a continuously conductive photoelectric surface is utilized on one side of the grid, and a photoelectric mosaic utilized on the other side on which a charge image may be formed to control electrons from the first surface.

In all cases high amplifications are obtained, the resultant electron image having a far greater intensity than an electron image originating directly from a photoelectric surface.

I claim:

1. A thermionic tube comprising an envelope containing means for producing an electron stream of picture area size and uniform cross-sectional density, an anode, a shield around said anode and having an aperture of elemental area in said stream, and an apertured grid of picture area size positioned between said electron producing means and said anode, said grid having a photoelectric mosaic on the surface facing said anode and a continuously conductive photoelectric surface on the opposite face thereof.

2. A thermionic tube having an envelope containing means for producing an electron stream having a cross section of picture area size, an apertured grid intersecting the entire cross section of said stream, and an anode positioned to receive only an elemental area of said stream after passing through said grid, said grid comprising a mesh fabric of conductive material, a layer of insulation on said fabric facing said anode, a mosaic of photoelectric material on said insulation, and a second photoelectric layer on the opposite side of said fabric.

3. A thermionic tube having an envelope containing means for producing an electron stream having a cross section of picture area size, an apertured grid intersecting the entire cross section of said stream, and an anode positioned to receive only an elemental area of said stream after passing through said grid, said grid comprising a mesh fabric of conductive material, a layer of insulation on said fabric facing said anode, a mosaic of photoelectric material on said insulation, and a second photosensitive layer on said fabric and electrically connected thereto.

4. A thermionic tube having an envelope containing means for producing an electron stream having a cross section of picture area size, an apertured grid intersecting the entire cross section of said stream, and an anode positioned to receive only an elemental area of said stream after passing through said grid, said grid comprising a mesh fabric of silver wire, a layer of insulation covering only the fabric surface facing said anode, the opposite face being bare, a photoelectric mosaic on said insulation, and a photosensitive surface on the exposed silver wires.

PHILO T. FARNSWORTH.

Oct. 7, 1941. P. T. FARNSWORTH 2,257,942

IMAGE AMPLIFIER

Filed April 5, 1939

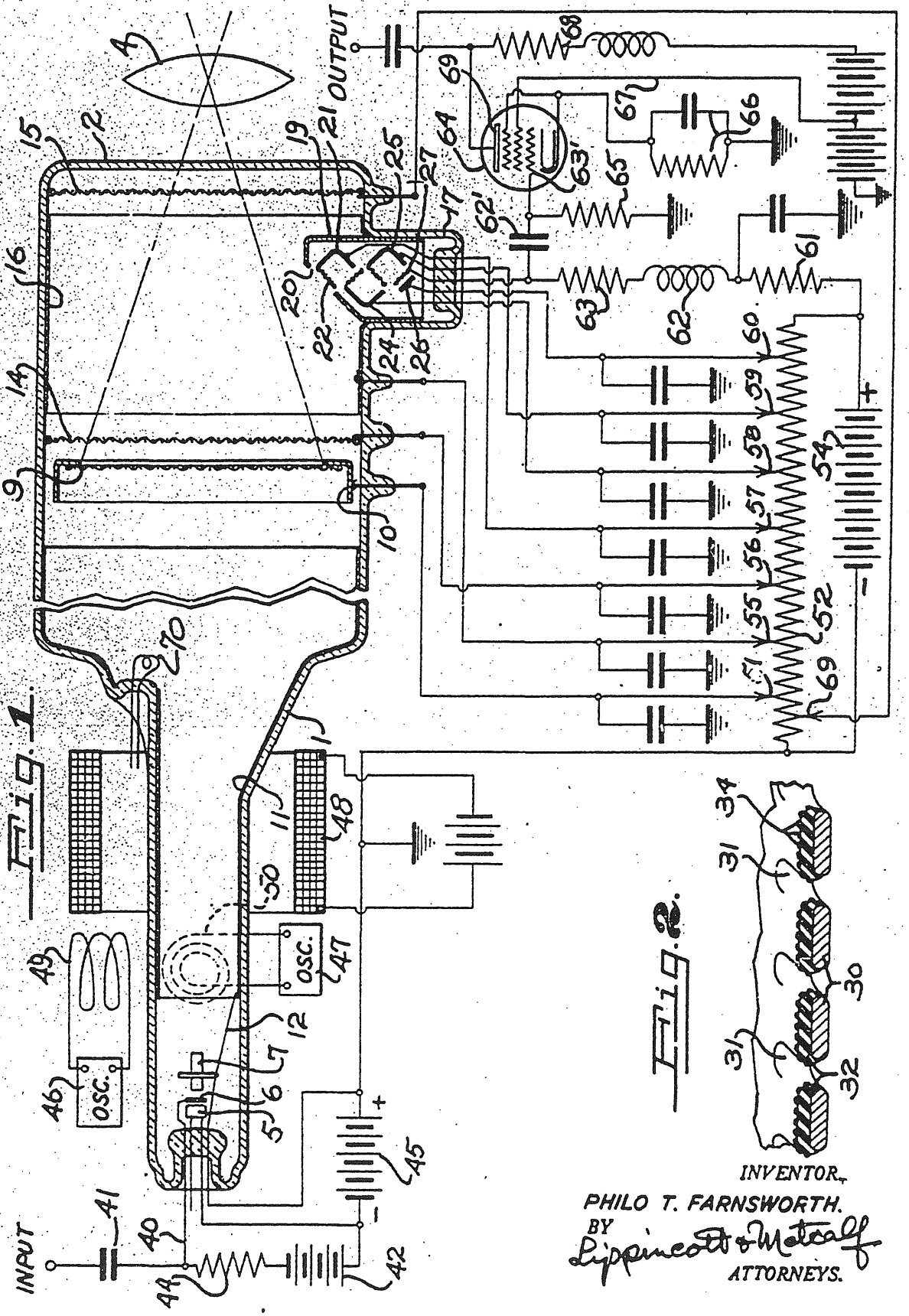

Fig. 1.

Fig. 2.

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Patented Oct. 7, 1941

2,257,942

UNITED STATES PATENT OFFICE

2,257,942

IMAGE AMPLIFIER

Philo T. Farnsworth, Philadelphia, Pa., assignor to Farnsworth Television & Radio Corporation, New York, N. Y., a corporation of Delaware

Application April 5, 1939, Serial No. 266,138

11 Claims. (Cl. 178—7.2)

My invention relates to image amplifiers, and more particularly to a means and method of obtaining a train of electrical signals representing an optical image. My system is particularly adapted for use in television.

Among the objects of my invention are: To provide an image amplifying tube of high sensitivity and fidelity; to provide an image amplifying tube and system for use in television transmitters; to provide an image amplifying system utilizing grid control of electron emission from elemental cathodes; to provide a means and method of producing a charge storage in an image amplifying tube; to provide a means and method of forming a charge storage electrode; to provide a means and method of controlling the storage time of a charge storage electrode; to provide a charge storage electrode adapted for use in an image amplifying television pickup system; to provide an image amplifying tube having a signal output well above inherent interference values; and to provide a means and method of operating a charge storage image amplifying tube and system.

My invention possesses numerous other objects and features of advantage, some of which, together with the foregoing, will be set forth in the following description of specific apparatus embodying and utilizing my novel method. It is therefore to be understood that my method is applicable to other apparatus, and that I do not limit myself, in any way, to the apparatus of the present application, as I may adopt various other apparatus embodiments, utilizing the method, within the scope of the appended claims.

Referring to the drawing:

Fig. 1 is a longitudinal sectional view, partly diagrammatic, showing one preferred form of my invention, together with a circuit by which the tube may be set into operation.

Fig. 2 is a perspective view, partly in section, showing one preferred form of charge storage electrode.

Referring directly to Fig. 1 for a description of a preferred form of my invention shown therein, an envelope 1 is provided at one end thereof with a planar window 2 through which light from an object may be projected by a lens 4. At the opposite end of the tube is positioned an electron gun which may be of conventional design, utilizing an indirectly heated thermionic cathode 5, a control grid 6, and an accelerating anode 7. Between the electron gun and the planar window 2, and coaxial therewith, is a charge storage electrode 9 mounted in a cup 10, the rim of the cup facing toward the electron gun. Between the cup 10 and the electron gun is a wall film 11 attached by a connection 12 to the anode 7 of the gun. Wall coating 11 approaches but does not connect with cup 10.

Between cup 10 and planar window 2, and immediately in front of charge storage electrode 9, is an accelerating screen 14, and a collecting screen 15 is positioned adjacent planar window 2. Both of these screens 14 and 15 are preferably of extremely fine wire in order that they do not greatly affect an optical image projected by lens 4 on charge storage electrode 9.

Positioned between screens 14 and 15 is a second wall coating 16 electrically separate from either screen, and at one side of the tube, connecting with the space between screens 14 and 15, is a multiplier tubulation 17. This multiplier tubulation 17 supports and positions a multiplier shell 19 having an opening 20 angularly facing screen 14 and charge storage electrode 9, but not extending into the optical path.

I may desire to utilize as an output device an electron multiplier, preferably of the box element type, such as described and claimed in the Richard L. Snyder application for United States Letters Patent entitled "Box element multiplier", Serial No. 149,654, filed June 22, 1937, now United States Patent No. 2,163,966 issued June 27, 1939. The first three stages are cube-shaped silver boxes. One face of each stage is open, and an adjacent face is also open but covered with a fine mesh tungsten wire screen. First stage 21 presents first-stage screen 22 across opening 20. The open side of first stage 21 is presented to the tungsten screen of second stage 24, and in similar fashion the open end of second stage 24 is presented to the screened side of third stage 25. An output screen 27 is positioned across the open end of third stage 25, and is backed by last stage 26 which is in the form of a planar silver electrode. The complete assembly thus described forms an electron multiplier, when sensitized for secondary electron emission, as described and claimed in the Snyder patent cited above.

Before describing the connections of the various elements in the tube shown in Fig. 1, I will describe, by reference to Fig. 2, the structure and formation of charge storage electrode 9. While I have found that various wire-mesh screens may be utilized for the foundation of this charge storage electrode, I have found it preferable to utilize a perforated nickel sheet 30 having approximately 160,000 perforations 31 per square inch, and approximately 0.0005 inch thick. The

nickel sheet may then be attached to cup 10 and placed in an evacuated evaporator in order that a film of refractory insulating material 32 may be evaporated on one side only thereof. This may be accomplished by utilizing the phenomenon that evaporation takes place along straight paths. The film of insulating material should have a low dielectric constant, be highly refractory, and be chemically stable. I have found that barium fluoride is representative of such materials, and this material is evaporated on one side of the nickel screen within an evaporating vessel by placing barium fluoride in a container approximately 6 inches from the screen, and heating the container.

I have found that a film of dielectric between 0.0003 and 0.0005 inch thick may be evaporated onto the nickel sheet in about five minutes. This process provides the dielectric coating 32, with the edges of this coating slightly overlapping the edges of the perforations in the nickel sheet, as shown in the sectional views of Fig. 2. I have also found that it is desirable to apply a tickler coil to the nickel sheet during the evaporation process in order to prevent too great an accumulation of barium fluoride on the sides of the perforations. Bulging sides at these points will greatly reduce the size of the openings in the sheet, which is, of course, undesirable.

The next step is to sputter a film of silver, indicated by globules 34 in Fig. 2, on top of the barium fluoride coating 32, preferably in an atmosphere of rarified oxygen. This silver film should preferably have extremely low conductivity approaching infinite resistance, and it has been found that less conductivity may be obtained by using oxygen than with any other gas.

The nickel screen with its dielectric and silver coatings may then be mounted in envelope 1, with the silvered surface facing the planar window 2 and with the nickel surface facing the electron gun. The other elements are then placed within the envelope 1 and the tube is degassed by baking for several hours at a high temperature. The silver film 34 is then oxidized in a glow discharge in the usual manner, well known in the art.

After cooling, the temperature is reduced to 200° C., and caesium is slowly distilled into the envelope 1 between the gun and the charge storage electrode 9 until the direct current photoelectric peak of the sensitized silver is just passed. The tube is then baked at 200° C. and baked for a short time until the peak value of photoemission is again reached. This procedure results in a mosaic photoelectric surface on the side of the charge storage electrode 9 facing planar window 2 and lens 4.

It will be obvious, however, that I have described just above only one method of obtaining a mosaic photoelectric surface, and I do not wish to be limited in any way to this particular method, as other methods and other materials may also be used to obtain the same result, as is well known in the art.

After the charge storage electrode 9 has been formed as just above described, the electron multiplier stages 21, 24, 25 and 26 may then be treated with suitable materials in order to obtain therefrom secondary electron emission at ratios greater than unity. Caesium treatment similar to that required to produce photoelectric surfaces may be applied to the multiplier stages directly through side tubulation 17 without affecting the sensitization of the charge storage electrode 9.

While there is another step, usually found desirable in the formation of the charge storage electrode 9, namely, the step of controlling the leakage time between the photoelectric mosaic 34 and the nickel screen 30, it is believed that a description of one type of circuit utilized to place the tube in operation will render the discussion of this final step more understandable. Accordingly, cathode 5 may be connected to a heating circuit in a manner well known in the art, in order that this cathode emit electrons. Grid 6 is connected by wire 40 through blocking condenser 41 to a signal input to which blanking impulses may be applied to extinguish the cathode ray beam during retrace intervals, and grid 6 is maintained at the proper biasing potential by bias battery 42 and bias resistor 44. Anode 7 is energized by anode source 45 at ground potential, source 45 placing the cathode 5 more negative than ground potential. Scanning oscillators 46 and 47 through scanning coils 49 and 50 move the electron beam emitted from anode 7 in two directions over a picture area on the nickel side of charge storage electrode 9, and focusing coil 48 is used to define the beam. The nickel screen 30 forming the foundation of this charge storage electrode is made more positive than anode 7 by means of a tap 51 on voltage-dividing resistor 52, this resistor being energized by the source 54. Multiplier housing 19 and connected film 16 are energized at the next higher potential by tap 55; accelerating screen 14 is held at the next higher potential by tap 56; first multiplier stage 21 is held at the next higher potential by tap 57; second multiplier stage 24 is held at the next higher potential by tap 58; third multiplier stage 25 is held at the next higher potential by tap 59; last stage 26 is held at the next higher potential by tap 60.

Output screen 27 of the multiplier is held at the highest potential through a final output circuit comprising a filter resistor 61, a choke coil 62 and an output resistor 63. Output screen 27 is also connected through a blocking condenser 62' to the control grid 63' of an output tube 64, the latter having a bias resistor 65, a screen bias connection 67, and an output resistor 68 connected to the anode 69 of output tube 64, all in the manner well known in the art for the connection of a screen-grid tube. Other output circuits are fully equivalent.

In operation the electron gun may be energized, for example, with a voltage of 500 to 1500 volts, to bombard the nickel side of the charge storage electrode 9. Some of the electrons in the gun beam, as it is scanned over the picture area on the nickel side of charge storage electrode 9, will pass through the perforations of the electrode and are collected on end screen 15 which is only slightly positive relatively to the gun anode 7, as indicated by end screen tap 69 on voltage divider 52. About 80% of the electrons in the gun beam, however, strike the metallic nickel surface of electrode 9 to produce secondary electrons.

I prefer to have a potential difference of from 5 to 50 volts positive on the accelerating screen 14 relatively to the nickel base of the charge storage electrode 9. This potential is insufficient, however, to draw any of the secondary electrons created by beam impact from the nickel side of the storage electrode 9 through the perforations of the storage electrode. However, when an optical image is focused on the mosaic side of the grid through a lens 4, photoelectrons are emitted

and drawn to screen 14, leaving the mosaic elements on the photoelectric side of storage electrode 9 charged positively with a charge that increases proportionally to the product of light intensity and time. This additional positive charge results in secondary electrons from the nickel side being pulled through the perforations in an amount which is proportional to the three-halves power of the voltage between the nickel surface and the photoelectric surface. It should be noted here that the control of each mosaic element is relatively large, since this mosaic element, acting as a grid, is only about one-thousandth of an inch from the source of the secondary electrons. The signal electrons are accelerated through screen 14 into the space between screens 14 and 15 and are drawn into the multiplier for multiplication therein.

We thus have a multiplicity of small amplifiers of which only those very near the area bombarded by the scanning gun beam have an emitting cathode. The current in the gun beam need not be more than a few microamperes, since this is quite adequate to give space charge saturation, for if a beam of elemental size is used and then multiplied by the number of picture elements, the effective cathode emission for the total number of elements may be on the order of an ampere or more.

It will be noted that the elemental grid elements, though effectively free under the conditions described thus far, are operated positively. It might be expected, therefore, that the grid current drawn by it would be excessive, and that the sensitivity would be decreased due to the rapid discharge of a grid element when the scanning beam was operating in its vicinity. Almost the opposite has been found to be true, however, and if a high potential difference is applied between screen 14 and the charge storage electrode 9, the beam discharge action is very low. Thus, the tube may be operated to have a "memory" or storage time of from five to ten minutes, thus rendering the tube practically useless for the transmission of moving objects but useful for other purposes.

Reducing the voltage applied between the screen 14 and the grid improves the speed of response and naturally decreases the sensitivity accordingly. In practice, the voltage difference is adjusted to be as high as possible without blurring of the field when the object moves. It is not necessary, however, that the elemental mosaic grid elements be operated free, as the leakage time may be controlled by evaporating the thin film of metal through the perforations in the grid from the nickel side until the time constants of the grid have the desired value. This effectively results in providing the grid elements around the perforations with a high-resistance leak across the edges of the insulating layer 32 at the edges of the perforations. In this manner the leakage time may be controlled as desired. If desired, a small nickel filament 70 may be positioned within the gun end of the tube and utilized during initial operation of the tube to control the leakage time. Other metals, such as magnesium or the like, may be used.

It should be noted that the potential of screen 14 is higher than the potential of multiplier shield 19 and attached wall film 16, but that the potential of first stage 21, presenting its screen 22 to the space between screens 14 and 15, is the highest positive potential acting on this space. Consequently, signal electrons passing through screen 14 are directed toward the multiplier input, pass through opening 20 and first-stage screen 22, and impact the sensitized surface of the first stage 21. Secondary electrons emitted by impact in first stage 21 are accelerated into second stage 24 to create more secondary electrons. These secondary electrons are accelerated into third stage 25 to create further electrons, and these latter are then accelerated to impact last stage 26. Secondary electrons emitted from the last stage 26 are collected by output screen 27, and the output current, comprising the signal current multiplied by repeated liberation of secondary electrons at a ratio greater than unity, is thereupon utilized in the output circuit in the usual manner for whatever purpose desired.

It has been found, experimentally, that signal electrons from all portions of the charge storage electrode 9 can be uniformly collected in the first stage of the multiplier with an efficiency of approximately 80%.

It should be pointed out also that one of the features of the present invention is the practical elimination of noise or irregularity in output due to the electrons of the scanning beam passing through the charge storage electrode 9. When no means are provided for collecting these primary-beam electrons to keep them from flowing in the output circuit, it is necessary that the component of signal current be at least 10% of the total beam current. Thus, if the beam current were to be 5 microamperes, the signal component would have to be at least 0.5 microampere; in other words, the sensitivity of the tube would be reduced approximately 10 to 1. However, by keeping primary electrons out of the work circuit by the use of the electron multiplier and the collection of scanning-beam electrons on screen 15, this reduction in sensitivity is entirely eliminated. Furthermore, the fluctuation voltage present on the elemental grid elements, that is produced by both thermal agitation and shot irregularities of the photocurrent, has a maximum frequency component in the neighborhood of ten cycles per second, and this frequency component is not passed by the external video-frequency amplifiers. Also, there is little or no shot noise in the multiplied current. The electron multiplier, therefore, may be utilized to increase the sensitivity of the tube by a factor of from twenty to one hundred times, not only without increasing the noise factors, but with actual reduction thereof because of the elimination of the scanning-beam electrons from the output.

The merits of the image amplifying tube and system described and claimed herein may therefore be summed up as follows:

(1) It provides a short optical system with the image plane perpendicular to the axis of the lens;

(2) No excessive power is required in the scanning beam;

(3) The electron beam scans the cathode perpendicularly;

(4) There is no shading compensation required; and

(5) My invention produces a light sensitivity several orders better than previous types of electronic scanning devices without increase in noise level.

I claim:

1. An image amplifier system comprising an envelope containing an electron-permeable charge storage electrode comprising a conducting foun-

dation, a layer of insulating material on one side only of said electrode, the other side of said electrode being capable of producing secondary electrons at a ratio greater than unity, and a mosaic photoemissive surface on said insulating material; means for focusing an optical image on said mosaic; electron producing and directing means for developing an electron beam of elemental cross-section impacting the secondary-emissive side of said electrode at a velocity sufficient to produce secondary electrons therefrom; means for scanning successive elementary areas of the impacted side of said electrode; means spaced from said electrode to collect beam electrons passing through said electrode; and separate means for collecting secondary electrons passing through said permeable electrode.

2. Apparatus in accordance with claim 1, with an accelerating screen positioned in front of said mosaic and energized to a potential insufficient to draw secondary electrons through said permeable electrode in the absence of light on said mosaic.

3. Apparatus in accordance with claim 1, with means positioned on the side of said permeable electrode remote from said electron beam producing means for collecting photoelectrons emitted from said mosaic surface.

4. Apparatus in accordance with claim 1, wherein the separate means for collecting the secondary electrons passing through said permeable electrode is an output electrode positioned between said mosaic and the means for collecting beam electrons, and positioned outside of the path of said beam electrons passing through said permeable electrode.

5. Apparatus in accordance with claim 1, wherein the separate means for collecting the secondary electrons passing through said permeable electrode is the first stage of an electron multiplier, said first stage being positioned outside of the path of beam electrons passing through said permeable electrode.

6. Apparatus in accordance with claim 1, with an accelerating screen positioned in front of said mosaic and energized to a potential insufficient to draw secondary electrons through said permeable electrode in the absence of light on said mosaic but energized to a potential sufficient to collect electrons emitted from said mosaic in the presence of light, said separate means for collecting secondary electrons being positioned between said accelerating screen and said means for collecting beam electrons and out of the path of beam electrons passing through said permeable electrode.

7. An image amplifier system comprising an envelope containing an electron-permeable charge storage electrode comprising a conducting foundation, a layer of insulating material on one side only of said electrode, the other side of said electrode being capable of producing secondary electrons at a ratio greater than unity, and a mosaic photoemissive surface on said insulating material; means for focusing an optical image on said mosaic; electron producing and directing means for developing an electron beam of elemental cross-section impacting the secondary-emissive side of said electrode at a velocity sufficient to produce secondary electrons therefrom; means for scanning successive elementary areas of the impacted side of said electrode; an accelerating screen positioned parallel to and adjacent said mosaic, a beam-electron collecting screen positioned coaxially with and parallel to said permeable electrode and said accelerating screen and spaced from said accelerating screen; and an output electrode positioned between said collecting screen and said accelerating screen and out of the path of beam electrons passing through said permeable screen and said accelerating electrode.

8. Apparatus in accordance with claim 7, wherein said output electrode is the first stage of an electron multiplier energized to a higher potential than either said accelerating screen or said beam-electron collecting screen to attract secondary electrons passing through said permeable electrode and said accelerating screen.

9. In a system utilizing an electron-permeable electrode having one side capable of producing secondary electrons at a ratio greater than unity and an opposite side carrying a photosensitive mosaic spaced from said electrode by an insulating film, the method of producing an electrical signal in response to a light image which comprises generating a primary beam of electrons of elemental cross-section, directing said beam towards a plane to produce secondary electrons thereat, moving said beam across said plane to produce a cloud of secondary electrons delineating a picture area, applying an accelerating potential from the other side of said plane insufficient to draw secondary electrons through said plane in the absence of electrical charges therein, creating a charge image in said plane by projecting an optical image thereon and removing photoelectrons emitted thereat, and collecting secondary electrons passing through said plane under the control of charges therein.

10. In a system utilizing an electron-permeable electrode having one side capable of producing secondary electrons at a ratio greater than unity and an opposite side carrying a photosensitive mosaic spaced from said electrode by an insulating film, the method of producing an electrical signal in response to a light image which comprises generating a primary beam of electrons of elemental cross-section, directing said beam towards a plane to produce secondary electrons thereat, moving said beam across said plane to produce a cloud of secondary electrons delineating a picture area, applying an accelerating potential from the other side of said plane insufficient to draw secondary electrons through said plane in the absence of electrical charges therein, creating a charge image in said plane by projecting an optical image thereon and removing photoelectrons emitted thereat, collecting beam electrons passing through said plane, and separately collecting secondary electrons passing through said plane under the control of charges therein.

11. Method in accordance with claim 10, wherein collected secondary electrons are multiplied by repeated secondary electron producing impacts.

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June 11, 1946. J. H. DEMING 2,401,723

METHOD AND APPARATUS FOR LOCATING OBJECTS

Filed Feb. 12, 1942 2 Sheets-Sheet 1

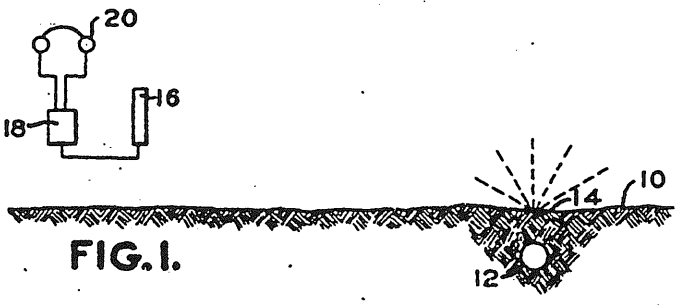

FIG. 1.

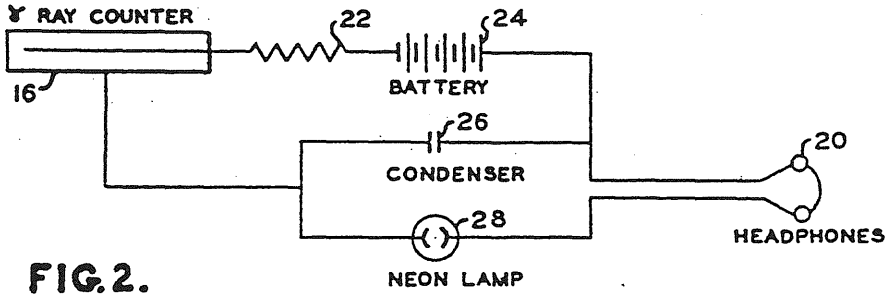

FIG. 2.

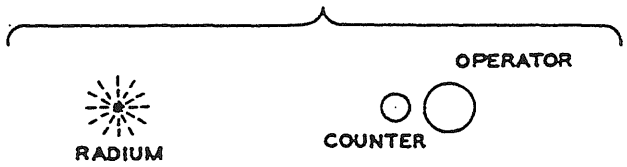

FIG. 5a.

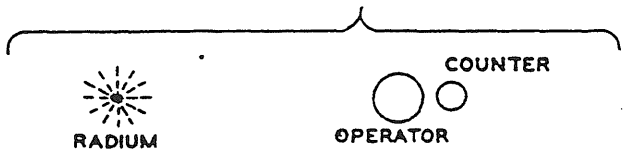

FIG. 5b.

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METHOD AND APPARATUS FOR LOCATING OBJECTS

Filed Feb. 12, 1942 2 Sheets-Sheet 2

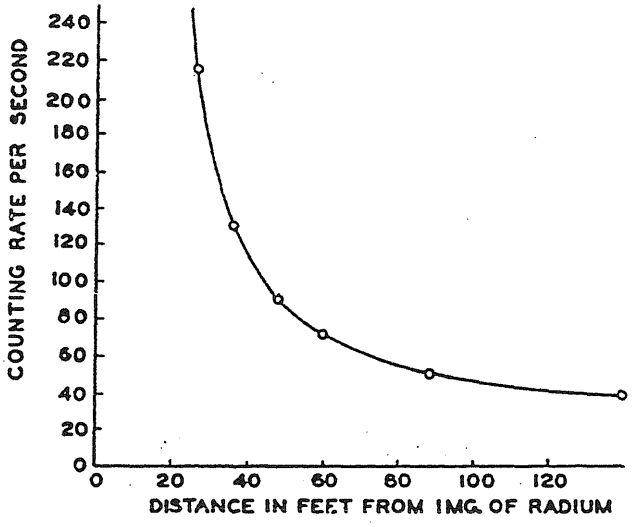

FIG. 3.

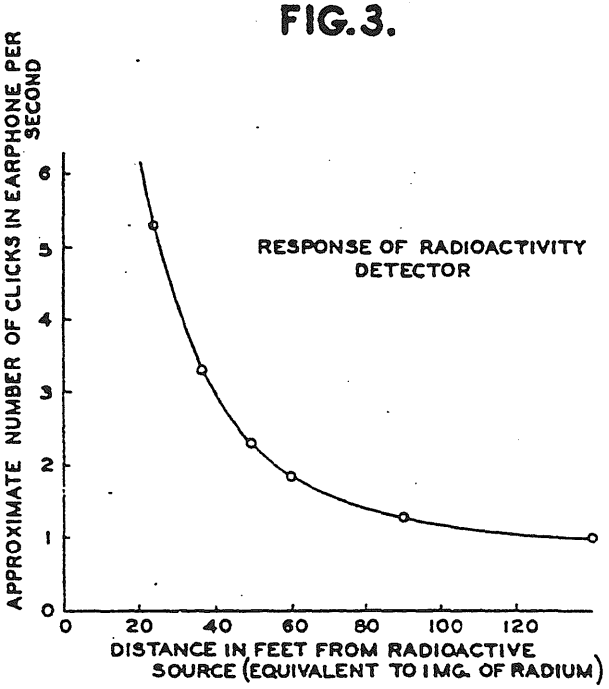

FIG. 4.

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Patented June 11, 1946 2,401,723

UNITED STATES PATENT OFFICE

2,401,723

METHOD AND APPARATUS FOR LOCATING OBJECTS

Joseph Horace Deming, Houston, Tex., assignor to Texaco Development Corporation, New York, N. Y., a corporation of Delaware

Application February 12, 1942, Serial No. 430,603

6 Claims. (Cl. 250—83.6)

1

This invention relates to the locating of lost or hidden objects and more particularly to a method and an apparatus for relocating land mines which have been previously buried or planted by a retreating army. The principal object of the invention is to provide such a method and apparatus by means of which a dangerous object, such as a hidden explosive mine, can be readily located so that it can either be removed or suitably marked.

It is well known that frequently troops retreating or moving from one position to another plant explosive mines, usually below the surface of the ground, so that the movement of motorized equipment such as tanks and large trucks in passing over the mined section will discharge these mines, thus disabling the equipment. It often happens that in reoccupying previous battle positions it is desirable to relocate and "sweep up" mines previously planted. This is obviously a difficult and dangerous procedure since the mines must in the first instance be planted in such a manner that their position would not be readily ascertained by the enemy. Certain methods have been tried out to accomplish this purpose. The explosive charge is usually contained in a housing of steel or other metal, and attempts have been made to locate these mines by using the so called "treasure finders" which utilize the principle that a body of metal or a metallic object in the general vicinity of the detecting instrument will cause a variation in some characteristic of an electric circuit to provide an indication to the observer that the metallic object is near. By walking around in the general vicinity of such an object, the observer can tell, as by a change in frequency of a note heard in a pair of earphones, the exact spot at which the object is located.

In accordance with the invention the land mine is constructed so that it preferably contains substantially no metal. The explosive may, for instance, comprise one or more sticks of dynamite or other such material suitably waterproofed and a percussion or detonating device suitably constructed with the use of hard wood, plastic or some other non-metallic material. Thus, once a mine constructed along these lines has been buried it cannot be subsequently located by means of the "treasure finder" type of instrument mentioned hereinbefore. In order, however, that those who have planted the mine can subsequently readily relocate it, I incorporate in each mine a small quantity of a radioactive substance, the presence and location of which substance can subsequently

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be determined through the use of an instrument sensitive to the radiation emitted by the substance. The radioactive material can be incorporated in the mine in any desired manner, as by the use of radioactive salts in the paint used on such mines. If a separate detonating device is used, the radioactive material can be attached to or housed within that device in any suitable manner. It is desirable that the radioactive material be as close to the surface of the ground as possible so that the greater part of the radiation will not be absorbed by the earth.

For a better understanding of the invention reference may be had to the accompanying drawings in which

Figure 1 is a vertical elevation through a section of the earth showing a buried mine and an instrument for detecting the location of the mine;

Figure 2 is a diagram showing the elements and the electrical connections for the detecting instrument;

Figure 3 is a curve showing the counting rates when one milligram of radium is set up at different distances from the detector;

Figure 4 is another curve showing the response of the detector as indicated by clicks in the earphones after being scaled down by the instrument shown in Figure 2; while

Figures 5*a* and 5*b* are diagrammatic illustrations showing the directional effect, or rather the shielding effect, of the body of the operator.

In Figure 1 of the drawings the earth's surface is indicated at 10 and a land mine or other object 12 is shown as buried a short distance below the surface. Preferably the mine is so constructed that it does not contain any appreciable amount of metal and thus an operator carrying one of the so called "treasure finder" instruments and moving about above the mine would have no indication of the existence or location of the mine, as has been explained hereinbefore.

While the mine 12 is being planted, or at such other time as the exact location of the mine is still known, a small quantity of a radioactive substance 14 is placed in a known position with respect to the mine and preferably directly above the mine, close to the surface of the earth, as is shown in Figure 1. As has already been stated, if desired, the radioactive material may be directly attached to the mine 12 or to any separate percussion device associated with the mine, but it is preferable that the radioactive material be at, or immediately below, the ground surface. A radiation detector or counter 16 is shown dia-

grammatically and is connected to a suitable instrument 18 which in turn has connected to it a pair of earphones 20 adapted to be worn by an operator. The detector 16 may be of the well known Geiger-Muller counter type, but it is preferred to use a high efficiency and rugged gamma ray counter of the type shown in either of the copending patent applications of D. G. C. Hare, Serial Nos. 364,020 and 412,617 filed November 2, 1940, and September 27, 1941, respectively. The gamma ray detector or counter which has been used in connection with the present invention is of the general type disclosed in the aforementioned pending application, Serial No. 412,617, and comprises a plurality of thin, parallel, separated plates connected together electrically to form a cathode and provided with one or more series of aligned openings through which fine wires are disposed, these wires being connected to form the anode. The cathode and anode are housed in a cylindrical casing containing a gas, such as argon, and the counter is connected in a circuit in such a manner that when a gamma ray enters the detector the discharge or tripping of the detector will influence the circuit to cause an indication to be given.

A diagram of an electrical circuit in which the gamma ray counter may be connected is shown in Figure 2. The elements shown in this figure with the exception of the counter and the earphones may be housed conveniently in a small box such as is shown at 18 in Figure 1. As shown in Figure 2, the anode and the cathode of the counter 16 are connected in series with an electrical resistance 22, a source of electrical supply such as the battery 24, and a condenser 26. A small gaseous discharge device, such as the neon lamp 28, and the pair of earphones 20 are connected in series across the condenser 26. It will be noted that the circuit, as shown in Figure 2, contains no elements such as radio tubes which will draw a heavy current from the battery. For this reason the battery supply will last for many months. The circuit shown in Figure 2 is not the only one that could be utilized in carrying out this method. Many others such as multi-vibrator circuits, Nehrer quench circuits, etc., will occur to those versed in the art.

In Figure 3 is shown the counting rates when one milligram of radium is set up at different distances from the detector. It will be noted that at considerable distances, i. e., about 150 feet, the source has little effect on the detector and the discharges are due to the radioactivity of the surrounding earth and to the effect of cosmic rays. The counting rate increases to twice the background value at a distance of 60 feet from the source and it increases steeply for smaller distances. The counting rate at 50 feet is about 70 counts per second and this rate would be too high for direct perception by the ear. With the circuit shown in Figure 2 the condenser and the neon lamp scales this number down so that only about one click is heard in the earphones 20 for every 50 discharges of the counter. The ear then perceives a counting rate of about two clicks per second at a distance of 50 feet from one milligram of radium. It is very easy to determine a change of frequency by a factor of two at these low frequencies and after some accommodation to the counting rates even changes of 50% can readily be detected. This scaling down of the number of clicks, as shown in Figure 4, has another important advantage. The discharges of the counter 16 occur at a random time distribution, and sometimes discharges follow each other very closely and then there may be a rather long interval between discharges. In order to evaluate the frequency of the counts the ear has to average these varying intervals and it must detect changes of the average counting rate. The scale circuit reduces this distribution to fairly regularly spaced clicks, and it is therefore much easier for the ear to observe changes of the regular counts.

In operation, it is merely necessary for an operator wearing earphones 20 and carrying the counter 16 and the instrument 18 to walk around in the general vicinity of the mine 12 and to follow the direction in which the clicking rates increase until the maximum counting rate is reached. This point will be, of course, the point of highest intensity of radiation from the source 14, and it will be known that the mine 12 is either directly below that point or is at a known position with respect thereto. The mine may then either be removed or a suitable marker may be placed in the ground to warn approaching tanks and other heavy equipment not to pass over that point.

Another feature of the invention is that an operator can easily obtain a directional effect with the equipment shown or, in other words, the body of the operator can be used as a shield for the gamma rays. Thus, as is indicated in Figure 5*a* where the operator is standing so that the counter is placed between him and the source, the counting rate may be, say, 4 per second. When the operator turns around so as to bring his body between the source and the counter, as is shown in Figure 5*b*, the counting rate will drop to about two clicks per second due to the absorption of gamma rays in the operator's body. The shielding effect allows the operator to find the direction in which the source is located and he need then merely walk in that direction until he reaches the point of greatest radiation intensity. In actual tests one-half a milligram of radium was planted in an unknown location in a field 25 yards square. It was found that an untrained person, using the equipment described, could find this source in from one to two minutes.

It is obvious that the size of the counter and the amount of the radioactive material should be chosen so as to be best adapted for the specific problem. In case there are no restrictions as the weight of the equipment, its sensitivity can be much increased and sources of radiation located from greater distances. Such equipment could be used for locating mines at sea from a mine sweeper.

It is not necessary that pure radium be used as the source. The refining process of radium is slow and expensive in its last stages. One could easily use radium from the early stages of its refining process and material which contains radium in a rather dilute form, such as a concentration of one milligram of radium dispersed in ten grams of carrier substance, would be quite suitable. This product would, of course, be substantially less expensive than pure radium.

Although a high efficiency gamma ray counter is preferred as the detecting device, the ordinary Geiger-Muller counter can be used in a similar manner, but, in order to obtain equal counting rates, its volume would have to be about 15 times greater than that of the counter disclosed, for instance, in the aforementioned pending application Serial No. 412,617. This naturally makes the equipment very bulky and furthermore the ordi-

nary Geiger-Muller counter would have a much higher background due to cosmic rays. This, of course, prevents the detection of weak gamma ray intensities.

The ionization chamber could also be used as a detector but it has the disadvantage that the electric currents generated in it by the gamma rays are extremely small. They can be perceived with a suitable electrometer but apparatus of this kind would be rather impractical. The small current could be increased by means of a suitable amplifier but such equipment is elaborate and requires the attention of well trained operators.

Obviously many modifications and variations of the invention, as hereinbefore set forth, may be made without departing from the spirit and scope thereof, but only such limitations should be imposed as are indicated in the appended claims.

I claim:

1. The method of locating a land mine buried in the earth which comprises placing substantially above and in a known position with respect to said mine a quantity of a radioactive substance when the mine is being buried, and subsequently determining the location of said mine by detecting at various points over the earth's surface in the general vicinity of the mine radiation emitted by said radioactive substance.

2. The method of locating a non-metallic land mine buried in the earth which comprises attaching to said mine a small quantity of a radioactive substance before the mine is buried or while its location is still known and subsequently locating the mine by detecting in the general vicinity of the mine the amounts of radiation emitted by said substance, said amount varying indirectly as the distance from the mine to the detector.

3. The method of locating a non-metallic explosive mine buried in the earth which comprises associating with said mine a small quantity of a substance capable of emitting gamma radiation before the mine is buried or while its location is still known and then subsequently locating the mine by detecting in the general vicinity of the mine the intensity of the gamma radiation emitted by the substance, said intensity varying indirectly as the distance from the mine to the detector.

4. The method of placing and subsequently locating an explosive mine formed of an explosive disposed in a casing which comprises utilizing a non-metallic material for said casing, associating with said mine a quantity of a radioactive substance, and subsequently determining the position of said mine by detecting radiation emitted by said substance and locating the point where the radiation has the greatest intensity.

5. The method of locating a buried explosive mine formed of an explosive disposed in a non-metallic casing which comprises placing a quantity of a radioactive substance at the surface of the earth in known position with respect to said mine, and subsequently determining the position of said mine by detecting radiation emitted by said substance, and locating the point of most intense radiation.

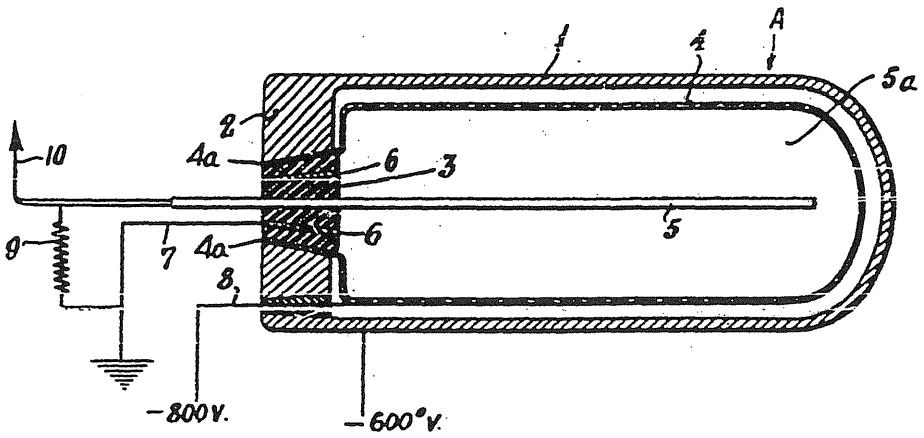
6. The method of locating a buried explosive mine near which has been previously positioned at a known location with respect thereto a quantity of a substance capable of emitting radiation, which comprises exploring the surface of the earth with a device capable of detecting radiation emitted by said substance, and locating the point at which the radiation has the greatest intensity, as indicated by said detecting device.

JOSEPH HORACE DEMING.

March 7, 1950 L. GOLDSTEIN ET AL 2,499,489

EXPLORING FOR RADIOACTIVE BODIES

Filed Jan. 24, 1944



Ladislas Goldstein and Boris Spiegel INVENTORS

BY Mocks Blum

ATTORNEYS

Patented Mar. 7, 1950 2,499,489

UNITED STATES PATENT OFFICE

2,499,489

EXPLORING FOR RADIOACTIVE BODIES

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Application January 24, 1944, Serial No. 519,506

5 Claims. (Cl. 250—83.6)

1

Our invention relates to a new and improved method of locating bodies of radio-active material, and an improved apparatus for this purpose.

The main object of our invention is to facilitate the discovery of deposits of uranium ores.

The uranium compound or compounds usually form only a small percentage of such deposits, usually about 1% by weight.

The present method of exploration is very slow and expensive.

According to our method, a suitable ionization chamber is transported over the territory to be explored, preferably by means of an aircraft. This is of great advantage in exploring large areas.

The annexed drawing illustrates the ionization chamber which we utilize. The invention is not limited to the details stated herein.

Such ionization chamber A is of general cylindrical shape. Its axial length is 100 centimeters, or about 40 inches. Its diameter is 20 centimeters, or about eight inches. The wall 1 of the chamber A is made of aluminum, duralumin, or other suitable metal or alloy. As an example, this wall 1 is maintained at a constant negative voltage of 600 volts. The base 2 of said chamber has a bore, which is closed gas-tight by a plug 3, which is made of insulating material. Said plug 3 and said bore of base 2 are of frusto-conical shape.

A conductive screen 4 is fixed to plug 3, or is otherwise held fixed in spaced relation from the interior surface of wall 1 and base 2. This screen 4 defines an inner ionization chamber 5a. Said screen 4 is insulated from wall 1 and base 2. The wall 1 usually contains a small percentage of radio-active material as an impurity, and such radio-active material emits alpha rays. It is desired to prevent such alpha rays from penetrating the inner ionization chamber 5a. The fixed spacing between screen 4 and the interior face of wall 1, therefore depends upon the pressure and composition of the gaseous filling. As an example, if the gaseous filling is argon, under a pressure above ten atmospheres, the spacing between screen 4 and the inner face of wall 1, including its base 2, is about five millimeters. Hence the volume of the ionization chamber 5a which is enclosed by screen 4, is substantially equal to the volume of ionization chamber A. In this example, said volume V is substantially 2,000 cubic centimeters. If the pressure P is 150 pounds per square inch, VP equals 300,000.

The wall 1 may be made originally in two or more transverse sections, so that the screen 4 and plug 3 may be located relative to base 2, in final relation. The other section of wall 1 can then be fixed to the section which is integral with base 2. A gas-tight joint, such as a threaded joint, is formed between sections of wall 1.

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An axial cylindrical electrode 5, whose diameter is about two millimeters, fits gas-tight in an axial bore of insulating plug 3. The chamber A is filled with a suitable gas, such as argon, under suitable pressure. This pressure may be thirty atmospheres, or about 440 lbs. per square inch. Said pressure may be as high as 100 atmospheres or even more. A frusto-conical conductive member 6 is located gas-tight in a bore of plug 3.

Said member 6 is a guard ring, which is maintained at zero potential by a wire 7, which is connected to a metal frame of the aircraft, or is maintained at zero potential in any manner. This guard ring 6 acts as a ground electrostatic shield for the respective adjacent part of the electrode 5. It also prevents any leakage of charge or current between the electrode 5 and the screen 4, or between the wall 1 and electrode 5. The guard ring 6 may extend longitudinally inwardly and outwardly from the insulating plug 3.

The screen 4 is maintained at a fixed high voltage, which may be either positive or negative. We prefer a negative voltage. The screen 4 is connected to the negative terminal of the source of biasing potential by wire 8. The positive terminal of the source of biasing potential may be grounded in the usual manner. As an example, the fixed or constant negative voltage of screen 4 may be 800–1600 volts. When alpha rays are radiated from wall 1, such alpha rays produce gaseous ions in the space between screen 4 and wall 1. The function of the charged screen 4 is to extract such ions, in order to prevent such ions from entering the inner ionization chamber 5a. It is well known that the ionization of a gas produces positive and negative particles or ions. If a gas is thus ionized between two electrodes which are at different respective potentials, the positive ions will move to the electrode of lower potential to be extracted, and the negative ions will move to the electrode of lower potential to be extracted. In this example, the wall 1 is maintained at a fixed negative potential of minus 600 volts. This can be done in the usual manner, by connecting wall 1 to the negative terminal of a source of unidirectional and constant voltage. The positive terminal of said source may be grounded, as is customary in providing a biasing potential. In this example, wall 1 is the anode and screen 4 is the cathode. If screen 4 and wall 1 were connected

by a wire, current would flow through said wire from wall 1 to screen 4. Hence the negative ions which are formed by the alpha rays in the gas between screen 4 and wall 1, will be extracted at wall 1 in this example, and the corresponding positive ions will be extracted at screen 4. Such ions will be extracted, as long as there is a suitable difference of potential between screen 4 and wall 1. Thus, if screen 4 is at a positive potential and wall 1 is at a higher suitable positive potential, the ions which are formed by the alpha rays between screen 4 and wall 1, will be extracted by said screen 4 and wall 1.

Externally to chamber A, electrode 5 is connected to wire 7, through a resistor 9, whose resistance is 4.10^{10} ohms, namely, 40,000 megohms. This resistance may, for example, be within a range of 10^{10} ohms and 10^{11} ohms. The free end 10 of electrode 5 is connected to any suitable direct current amplifier.

The wall 1 and the electrode 5 form a small capacitance, whose capacity is about 25 micromicrofarads, namely, 25.10^{-12} farads. If C designates the capacity of said capacitance, and R designates the resistance of resistor 9, then CR is the time constant of the circuit. In this example CR equals one second. The time constant can be varied, but it preferably should not greatly exceed one second. In a capacitance-resistor circuit, the time constant is defined as being the number of seconds required to impress 63.2% of the full charge upon the capacitance, after a unidirectional and constant voltage is applied to the capacitance-resistor circuit. In this example, the constant charging voltage is 600 volts, because electrode 5 is maintained at zero potential, and wall 1 is maintained at a negative potential of 600 volts. The charging current must flow through resistor 9, which is connected in series to the capacitance which is provided by electrode 5 and wall 1. The electrode 5 and screen 4 provide another capacitance, which is connected in series with resistor 9.

This chamber A can be transported over the territory which is to be explored, in an aircraft, at a low altitude, which may be about 100 meters, or about 330 feet, at a low horizontal or ground speed, which may be about 100 feet per second.

When the chamber A is at this altitude, it will receive any gamma radiations from an area which has a radius of about 100 meters, namely, from an area of about 30,000 square meters, above whose center said chamber A is located.

If said area has a deposit of uranium ore, which is equivalent to one per cent of uranium oxide by weight, and if the area of said deposit is at least 100 square meters, such deposit will be detected by chamber A. The detecting apparatus will indicate a maximum ionization current, when the chamber A is substantially above this deposit, making allowance for the time delay of response to ionization. As the aircraft approaches said deposit, the ionization current will increase. As the aircraft moves away from said deposit, the ionization current will decrease.

In order to detect such a deposit, it need not be a continuous deposit. Such deposit may consist of separate adjacent deposits.

The gamma rays of such a deposit will penetrate the atmosphere through said height of about 100 meters, and such gamma rays will also penetrate wall 1 and pass into the inner ionization chamber 5a which is defined by screen 4.

There is always some ionization in the ionization chamber 5a which is defined by screen 4, because of cosmic rays and other penetrating radiations.

In this example, a potential difference of 800 volts is maintained between screen 4 and electrode 5, and screen 4 is negative relative to electrode 5. When the gamma rays ionize the gas between electrode 5 and screen 4, an ionization current will flow through the gas between them, so that the positive ions are extracted at screen 4 and the negative ions are extracted at electrode 5. This provides a detecting ionization current between the grounded point of electrode 5, and the source of biasing voltage whose negative terminal is connected through wire 8 to screen 4. This detecting current will increase or decrease as the ionizing effect of the received gamma rays increases or decreases. In effect, the gamma rays vary the resistance of the circuit of the detecting ionization current between electrode 5 and screen 4. When the aircraft approaches a source of gamma rays, the detecting current will increase, and such detecting current will decrease as the aircraft moves away from the source of gamma rays. Due to the corresponding change in effective resistance of the gas between electrode 5 and screen 4, there will be a variation in the potential of the point of electrode 5 which is connected to resistor 9, with a corresponding variation in potential at point 10 of electrode 5.

Hence, the ionization current, in this example, will detect the presence of a commercial uranium ore deposit, in a belt which extends laterally 100 meters at each side of the course of the aircraft. The period of each indicating pulse of the ionization current, in which it rises to a maximum from a minimum value and in which it is reduced to said minimum value, depends upon the ground speed of the aircraft, allowance being also made for said time constant, CR.

If the aircraft is flown over the territory to be explored at the low ground speed of about 100 feet per second, the voltage of electrode 5 at point 10 will thus be varied by an average uranium deposit of commercial value, during a respective detection period of about three seconds. The detecting variation in voltage of electrode 5 at point 10 can be amplified by a conventional direct current amplifier, whose current variation can be continuously recorded by conventional means, or transformed to an A. C. voltage and thus amplified by a conventional A. C. amplifier. Each detecting voltage pulse of electrode 5 at point 10 thus produces a detecting current increase pulse, during a few seconds, in the output of the amplifier.

During each detecting pulse, the voltage of electrode 5 at point 10 passes through a maximum. This variation in voltage can be used to produce an alternating current by conventional means, and such alternating current can be amplified and detected. Such voltage pulse can be separated into shorter pulses, by using a suitable interrupter or chopper.

The altitude of the aircraft is suitably determined and recorded by using an altimeter, because the intensity of the gamma radiation which is received from the ground, depends on the altitude of the aircraft.

Hence, at the end of an exploration flight, each detecting current pulse or voltage pulse which is delivered by the amplifier will have been detected and recorded. A suitable record is simultaneously and continuously made of the explored territory, as by a continuous series of pictures, so that

each detecting current pulse can be identified with the respective area of the explored territory.

As previously stated, the cosmic rays and stray radio-active rays will always produce some ionization in the chamber 5a, so that current will always flow from the point of zero potential to electrode 5, in this example.

If the gaseous filling is argon, and VP equals substantially 300,000 in chamber 5a, as previously stated, the normal stray-ionization current is about 2.10^{-13} ampere, namely, about 0.2 micro-microampere. In such case, if the potential difference between electrode 5 and screen 4 is 800 volts, the potential of electrode 5 is changed from zero potential by $.8.10^{-3}$ volts, namely, 0.008 volt, because substantially the entire voltage drop of the stray ionization current is through the gas between electrode 5 and screen 4. Since the screen 4 is substantially of the same size as wall 1, there will be little difference between the time constant of the circuit of the capacitance 5—4, and the circuit of the capacitance 5—1, since the resistor 9 is common to the circuits of 5—4 and 5—1.

By providing the screen 4 with a higher negative potential than wall 1, we suppress or minimize the effect of alpha rays which are emitted by wall 1.

There is no discharge between wall 1 and screen 4, because the compressed gas can easily withstand a voltage difference of 200 volts.

Even if the surface of the ground is irregular, or if the altitude of the aircraft is varied within reasonable limits, the presence of a commercially workable uranium deposit will produce a substantial and easily detectable increase of at least 20% in the current which is delivered by the amplifier.

The invention is not limited to the details stated herein. By diminishing the CR factor, we can use an aircraft which operates at higher speed. The axis of the chamber A is held horizontal.

The invention applies to the detection of uranium ore deposits which are at or close to the surface of the ground, so that the gamma rays can enter the atmosphere.

Our invention is useful for detecting any source of gamma rays, such as a plant which has large quantities of radium compounds, uranium compounds, etc.

The correlation of the various factors is one of the features of our invention. The CR factor must be in proportion to the speed of the aircraft. The time factor, CR, must be regulated so that a perceptible pulse of ionization current is secured during the scanning period. Instead of making a photographic record of the explored territory, maps and other means can be used for determining the region of the deposits. The current of the amplifier can be designated by a suitable continuous graph, on a conventional recording device. By plotting the course of the aircraft with reference to a map, and thus recording the direction of movement of the aircraft and its speed, it is possible to ascertain the position of the aircraft during each instant of time. The altitude of the aircraft should also be continuously determined and recorded.

Upon comparing this with the ionization current graph, which is also plotted with reference to time, the desired data can be determined.

The screen 4 may have a frusto-conical extension 4a, which is made of insulating material, and which is clamped between base 2 and plug 3. Any other means may be used for supporting screen 4 in fixed spaced relation from wall 1, and insulated from wall 1.

The undesired radiations, such as cosmic rays, internal alpha rays, gamma radiations from the ground which are found even in the absence of any substantial mass of radio-active material, etc., are conveniently designated as stray radiations. Electric charge is withdrawn from the electrode 5 at a sufficient rate, either wholly to compensate for such stray radiations, or sufficiently to compensate for such stray radiations, to detect a voltage change on electrode 5 which corresponds to a predetermined intensity of gamma ray radiation.

The gaseous filling of the chamber is preferably free from water vapor.

We have described a preferred embodiment of our invention, but it is clear that numerous changes and omissions and additions can be made without departing from its scope.

We claim:

1. A method of detecting the presence of a mass of radio-active material which emits gamma rays and which is located sufficiently close to the surface of the earth to emit said gamma rays upwardly into the atmosphere, which consists in moving an aircraft over the region to be explored, said aircraft being thus moved at an altitude within the upward range of said gamma rays, supporting a detecting ionization chamber on said aircraft to receive said gamma rays within said ionization chamber, maintaining a gaseous filling in said detecting ionization chamber in excess of normal atmospheric pressure, maintaining a difference of potential between the wall of said detecting ionization chamber and an internal electrode thereof to extract the ions which result from said gamma ray ionization so that said ions are extracted at said wall and at said internal electrode to produce a flow of detecting ionization current between said wall and said internal electrode in a predetermined circuit relative to said internal electrode, substantially shielding said detecting ionization chamber from alpha rays, determining the stray ionization in said detecting ionization chamber which results from cosmic rays and other stray rays by determining the respective stray ionization current in said detecting ionization chamber which corresponds to the stray ionization which is produced by said stray rays, observing the increase in the flow of said detecting ionization current which is produced by the gamma ray radiation which is to be detected, said aircraft being moved at a speed which is sufficiently low in proportion to CR to produce said increase in said flow of current during a period which can be readily observed, C being the capacity between said wall of said detecting ionization chamber and said electrode, R being the resistance of the circuit in which said detecting ionization current flows.

2. An ionization device for detecting gamma rays, said device comprising an enclosed chamber which has a metal wall which is permeable to gamma rays and which emits alpha rays, said metal wall having an opening which is closed by a plug which is made of insulating material, said chamber having an ionizable gaseous filling, a perforate metal screen which is permeable to gamma rays, said screen being located in said chamber and being spaced from and being insulated from said metal wall, said screen substantially enclosing a part of the inner space of said chamber to provide an inner

ionization chamber, means maintaining said metal wall and said metal screen at a difference of potential which is sufficient to produce an ionization current through said gaseous filling between said metal wall and said metal screen by extracting ions which are produced by said alpha rays in said gaseous filling in the space between said wall and said screen, said gaseous filling being under sufficient pressure to limit said ionization current between said wall and said screen to the ionization current which is produced by the extraction of said ions, an electrode extending outwardly of said enclosed chamber and said ionization chamber through said plug, said electrode being connected through a resistor to a point whose potential is different from the potential of said screen, the CR factor of said ionization device being at least substantially one second, C being the capacity between said wall and said screen, R being the resistance of said resistor.

3. A device according to claim 2, in which said screen is negative relative to said wall and said electrode.

4. A device according to claim 2, in which said metal wall is maintained at a negative potential, said screen is maintained at a greater negative potential than said wall, and said electrode is connected through said resistor to a point of zero potential.

5. A device according to claim 2, in which said screen has an extension which is made of insulating material and which is fixed between said plug and said metal wall, a metal shield being located in said plug between said electrode and said extension, said shield being connected to said electrode through said resistor.

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BORIS PREGEL.

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June 19, 1951 C. F. TEICHMANN 2,557,158

RADIOACTIVE EXPLORATION

Filed Nov. 30, 1948

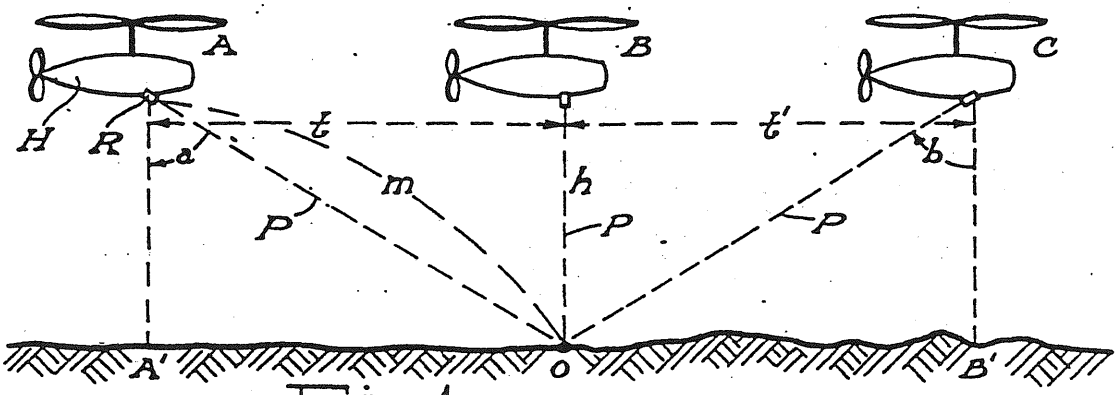

Fig. 1.

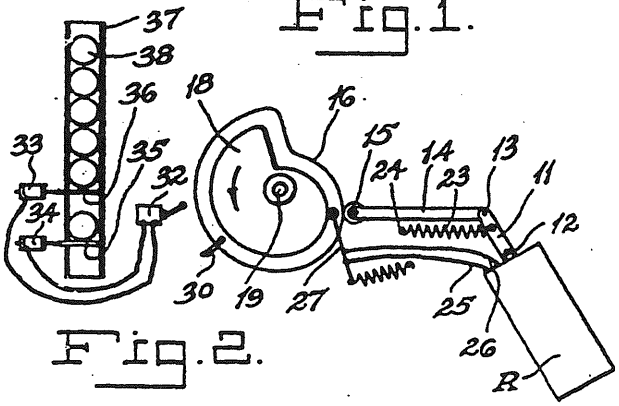

Fig. 2.

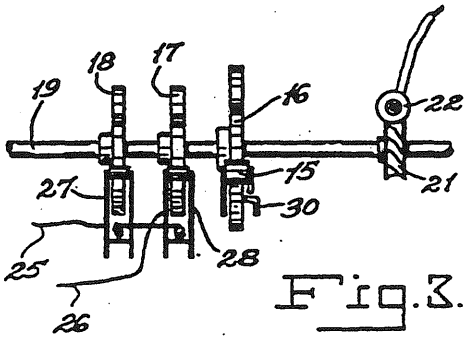

Fig. 3.

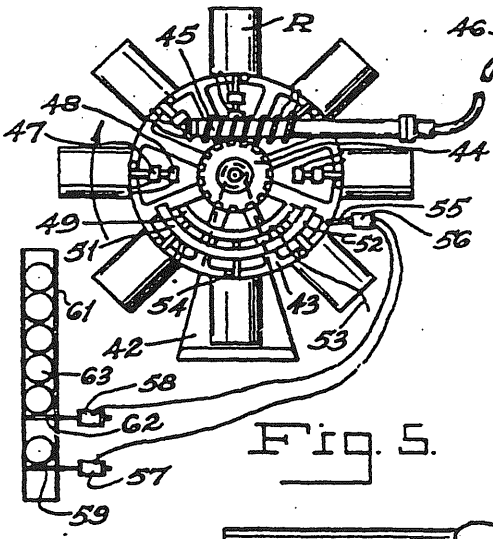

Fig. 5.

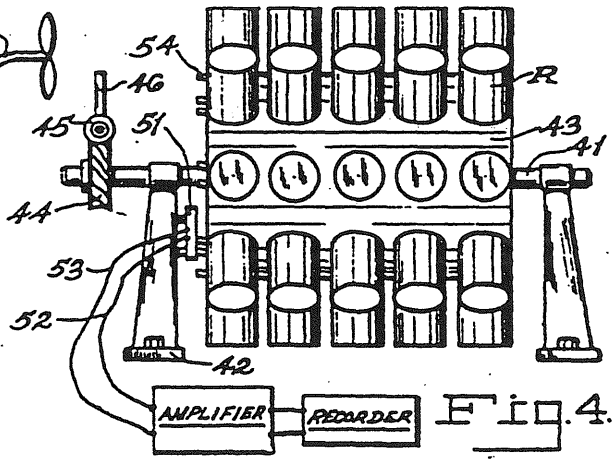

Fig. 4.

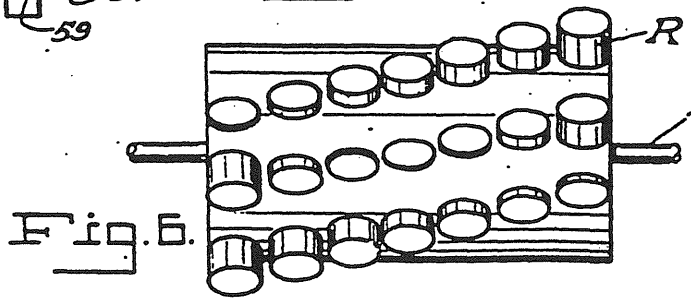

Fig. 6.

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Patented June 19, 1951

2,557,158

UNITED STATES PATENT OFFICE

2,557,158

RADIOACTIVE EXPLORATION

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Application November 30, 1948, Serial No. 62,779

10 Claims. (Cl. 250—83.6)

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This invention relates to radioactive exploration such as is utilized in prospecting the earth's surface for mineral deposits.

To date a number of methods have been proposed for prospecting by the measurement of radiation such as gamma rays above or beneath the surface of the earth.

One method involves the taking of measurements on or above the earth's surface as from a moving vehicle. With this method, the detector is continuously scanning the ground, and to produce worthwhile data, it should be of an exceedingly sensitive type such as those disclosed in Patent Nos. 2,390,071 and 2,390,072.

Moreover the data is of a semi-integrated nature in that the readings are not taken at a fixed point over an appreciable time interval but at a series of fixed points, each over a very short time interval. At any one point, the time interval afforded for the reading is extremely short. While such readings are of value, it is desirable under some circumstances, as when relatively small or narrow anomalies are encountered or when relatively insensitive detectors are used, to obtain readings of a series of fixed points or sections, each reading being taken over an appreciable time interval.

One object of this invention is the provision of a novel method of radioactive exploration wherein the advantages of measurements over appreciable time intervals of a series of fixed points or sections of the area being explored are combined with the economies of a continuously moving exploration.

Another object of this invention is the provision of novel apparatus for practicing the above method.

Another object of the invention is the provision of a novel method of making radioactive surveys wherein large areas can be quickly surveyed and the results of the surveys correlated with the terrain with a high degree of accuracy.

Further objects and advantages of the invention will be apparent from the following description and claims taken in connection with the attached drawings wherein.

Fig. 1 is a diagram illustrating a method of practicing the invention;

Fig. 2 is a simplified showing in side elevation of one form of apparatus for practicing the invention;

Fig. 3 is an end elevation of the apparatus in Fig. 2;

Fig. 4 is a side elevation of a modified form of apparatus;

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Fig. 5 is an end elevation of the apparatus of Fig. 4;

Fig. 6 is a modification of the apparatus shown in Figs. 4 and 5.

One feature of the present invention involves an improvement in radioactive exploration wherein the exploring means is moved substantially continuously over the area to be explored and simultaneously ranged for observation for appreciable time intervals on a series of predetermined fixed points or sections in the area. More specifically the use of a radiation detector on a moving support is contemplated, the detector being mounted for synchronous movement relative to the support whereby it can be ranged on a predetermined point or section of the area being explored and maintained on that point during movement of the support for an appreciable time interval. The support in question may be a vehicle moving over or beneath the surface of the earth or an aerial vehicle such as a helicopter moving above the earth's surface.

Another feature of the invention involves improvements in radioactive survey methods wherein measurements can be made over a large area in a relatively short time and the area marked at the same time, the markings being subsequently correlated with the area and the measurements correlated with the markings. More specifically it is contemplated that measurements, either of the continuous or intermittent type, be made of the area being surveyed and that the area be suitably marked with visible markings at the same time whereby the area with its markings can be photographed and the measurements correlated with the markings and the area. Continuous photographing of the area coincident with the radioactive surveying is also contemplated, either with or without the use of suitable markings.

Before entering into an explanation of the invention, it is advisable first to review the general characteristics of the detectors suitable for use. The principles of operation of such detectors are well known. They are made in different shapes and unless shielded are sensitive to radiation from all directions. While shielding of the detector as by suitable metal may not entirely eliminate its sensitivity to all surrounding radiation, the shielding is effective to a degree such that when it is positioned predeterminately and in an appropriate arrangement, the detector can be said to posses a principal axis of sensitivity, i. e., an axis which extends through an unshielded area or opening through which considerably more

radiation can enter the detector than through the shielded areas. Thus a detector can be said to be capable of directional control, that is, the detector can be directed or ranged so that this principal axis of sensitivity is directed upon a particular area or zone that it is desired to observe. While some radiation from the surrounding area will pass through the shielding and register on the detector, the amount of this radiation is relatively small, and it can be said properly that the measurements being taken are reasonably accurate measurements of the particular area or zone under observation. Obviously with shielding of proper design, a detector of any shape can be modified to develop the desired principal axis of sensitivity.

The basic principle of the point survey feature can be explained by reference to Fig. 1 wherein three steps in the progress of an aerial survey are illustrated. If the helicopter H, selected for purposes of illustration, is flown over the area indicated and the radiation detector R is held at a fixed position with respect to the helicopter with its principal axis of sensitivity P pointed toward the earth's surface, a continuous reading from point A' to point B' will be made, the reading at each increment of distance being made in a relatively short time. In a good many instances the readings so obtained are satisfactory provided that highly efficient detectors be employed. Such detectors are disclosed in U. S. Patents Nos. 2,390,071 and 2,390,072 and are of a multiple cathode type. The cathode comprises a stack of perforated discs disposed coaxially and spaced parallel to each other with one or more anode wires running through the perforations transversed to the disc surfaces. The large cathode area per unit of an active volume thus obtained increases the efficiency for gamma rays several times without proportionally increasing the efficiency for the detector of "background." Counters of this type have a gamma ray counting efficiency of about 500% that of the conventional Geiger-Mueller counter.

In the event it is desired to use a counter of low sensitivity or it is desired to obtain reading intervals of greater time, the present invention is of advantage. To illustrate, if detector R be adjusted at position A so that its principal axis of sensitivity P is ranged on the predetermined point or section O and, during the travel of the helicopter from point A to point B, detector R is moved relative to the helicopter and in proportion to the speed of the helicopter through angle a in the direction indicated, axis P of the detector will continue to range upon point O and the detector will in effect take a reading as if it were substantially fixed with reference to point O during a time of travel t of the helicopter from point A to point B. During the next increment of travel of the helicopter from point B to point C during time t', detector R is moved at a rate proportional to the movement of the helicopter through angle b in the direction indicated, thus maintaining axis P of the detector ranged on point O.

On the helicopter reaching point C, detector R is returned to its initial position as shown at A so that its axis P is ranged on a new point or section for another measurement, the subsequent movement of the detector relative to the helicopter being synchronized as already explained.

There is some slight variation in the extent of the observed area during the observation period because of the changing angle between the principal axis of sensitivity of the detector and the plane of the ground surface. For example, if it be assumed that the observed area at O when the detector is in position B is in the shape of a circle, that circle will be elongated into an ellipse when the detector is in positions A and C. However, the error introduced thereby is substantially constant for all readings and can be disregarded. It can also be held to a minimum by reducing the distance A—C to a minimum and increasing h to an amount not incompatible with good observations.

The reduction in length of axis P as the detector moves from A to B and the increase in length of the same axis as the detector moves from B to C will cause some variation in reading. However this variation will be substantially constant for all readings and can usually be disregarded. Other variations may occur when a helicopter or other aerial vehicle is used by reason of slight changes in altitude. In such cases, the readings will be from areas of slightly different extent than those originally planned.

From the above it is evident that the detector is ranged on point O for a time interval equivalent to $t+t'$ which is appreciable compared to the very short observation interval at any one point achieved by holding the detector fixed relative to the helicopter. For example, if it be assumed that the helicopter is traveling at 30 miles per hour (44 ft. per second), each of angles a and b be taken as 45°, and the altitude h of the helicopter be taken as 150 ft., the distance from A to B or B to C is equal to h or 150 ft., the total distance from A to C being 300 ft. At a speed of 44 ft. per second,

$$t+t'=\frac{300}{44}$$

or 6.8 seconds. If the point or section O be assumed to be 10 ft. in length, the time of observation of a detector fixed relative to the helicopter would be

$$\frac{10}{44}$$

or only 0.25 second. Thus an increase of about 2700% in the observing interval is obtained while still permitting the helicopter to travel at the same speed. Moreover, the detector is ranged on a definte point during the observing period which is not the case with a fixed detector on a moving support which is always moving relative to the points being observed.

Obviously the rate of change of position of detector R relative to the helicopter can be varied as desired so that the length of the observation period can be correspondingly varied. With conventional detectors such as the Geiger-Mueller detector having relatively low efficiencies, the time interval will necessarily be longer. With more sensitive detectors, the time interval can be shortened or better readings obtained for the same time interval.

It will be noted that by maintaining the helicopter at a relatively constant speed and synchronizing the movement of detector R therewith, various points O at predetermined distances from one another can be observed, the points being substantially the same distance apart. The distance between points O can be predetermined by varying the rate of movement of the detector or changing the speed of the helicopter. It is contemplated with detector R fixed upon a point O, that the point be marked or identified by meth-

ods hereinafter explained, so that the resultant readings can be made the basis of an accurate grid of the area being prospected, reference to specific points on the grid being thereafter made by inspection of the markings.

To facilitate identification of the marked points, it is contemplated that they be marked by markers of different colors, for instance 5 colors which may be used in the same successive order throughout the entire prospecting. Alternatively every fifth point can be marked with a marker of one color such as red, the four intervening points being marked with markers of another color such as yellow.

As hereinafter explained, it is contemplated that the markers be applied in synchronism with the observation by the detector, preferably at the beginning of each observation cycle so that the markers will be close to the points being observed.

With a ground vehicle operating as a support for the radiation detector, the marking will be very accurate and no necessity for correction will be required. With a helicopter or other aerial support, it will be necessary to determine the error introduced by the fall of the marker from the helicopter and correct therefor. Since such exploration is conducted at relatively low altitudes, the error will be small and substantially constant.

The marking from the air can be accomplished in a number of ways. Markers of solid material, darts having colored streamers thereon, or packages of colored material such as paint or powder contained in frangible wrappings or containers can be dropped. The advance position from which the marker should be dropped to designate a selected point can be determined by the following well-known formula, neglecting resistance to air, wind currents, etc.

$$D = \text{the speed of the helicopter (ft./sec.)} \times \sqrt{\frac{2h}{g}}$$

With a speed of 44 ft. per second and an altitude of 150 ft.,

$$D = 44 \times \sqrt{\frac{2 \times 150}{32.2}} = 134 \text{ ft.}$$

In view of the low altitude, errors due to the resistance of the air, wind, etc. are very small and can be determined by a few trial drops. A satisfactory marking at an altitude of 150 ft. usually can be accomplished by dropping the marker at position A which represents the beginning of the run, the marker following the path indicated at *m*.

While it is to be understood that the method thus far described may be practiced manually by ranging he detector by line of sight on point O and dropping the marker at position A, it is preferred to accomplish such operations automatically.

Figure 2 illustrates one means by which this can be accomplished automatically. Figure 2 is a side elevation of an assembly designed to be mounted suitably on the moving support such as a helicopter by means not shown. Detector R is secured on one end of an arm 11 pivoted about a fixed axis 12, the upper end of the arm being connected by a pin 13 to a link 14 having a cam roller 15 arranged to ride on the surface of a cam 16. Cam 16, together with smaller and similarly-shaped cams 17 and 18, is mounted on a shaft 19 to which is secured a worm gear 21. Worm gear 21 is driven by a worm 22, the latter being driven in turn by any suitable means synchronized with the speed of the helicopter. The synchronized drive may be obtained by an electrical drive connected to worm 22, the speed of which is controlled by the air speed indicator of the plane. Or a wind motor may be positioned on the helicopter and connected to worm 22 through suitable gearing. A spring 23 fixed at 24 is provided to insure the pressure of cam roller 15 against cam 16.

Leads 25 and 26 from detector R are each connected to spring pressed arms 27 and 28 having cam rollers thereon in contact with the surfaces of cams 17 and 18, the latter being electrically connected to suitable amplifying and recording means as well known in the art. The radial faces of cams 17 and 18 are insulated as with rubber or suitable plastic.

Cam 16 mounts a projecting arm 30 thereon arranged to operate a switch 32 connected to solenoids 33 and 34, arranged to operate gates 35 and 36 within a magazine 37, solenoid 33 being provided with a dashpot or equivalent delay means to effect its operation of gate 36 from a closed to open position and vice versa after the same cycle of gate 35. Magazine 37 is filled with a suitable charge of markers such as balls 38 of frangible material containing paint or powder of a color that will contrast with the color of the area being surveyed.

In operation, shaft 19 is driven at the desired synchronized speed through worm assembly 21 and 22, cams 16, 17 and 18 revolving therewith in counterclockwise direction as viewed in Fig. 2. In the position shown in Fig. 2, the radiation detector is being caused to move in a clockwise direction about pivot 12 to hold its principal axis of sensitivity on the desired point on the earth's surface. At the same time leads 25 and 26 are connected through cams 17 and 18 to the associated amplifying and recording apparatus. With continued rotation of cam 16, the radiation detector will continue to be swung in a clockwise direction until the radial surface of the cam is reached whereupon cam roller 15 will be pressed toward the left by spring 23 and radiation detector R returned to its original position in a very short period of time whereupon the observing of another fixed point or section O is initiated. It will be noted that by reason of the insulated radial faces of cams 17 and 18, the detector is disconnected from the amplifier and associated apparatus during the return movement.

In the rotation of cam 16, projection 30 is so positioned on the cam that it contacts switch 32 to release a marker 38 therein through gate 35 at substantially the same instant that radiation detector R is first fixed upon point O. Gate 35 then closes whereupon gate 36 operates to reload the chamber between the two gates.

Obviously mechanical arrangements for discharging other types of markers such as darts may be connected for synchronized operation with cam 16.

For better coverage of the area being surveyed, it is usually desired to employ more than one radiation detector whereby a number of fixed points O can be measured instead of only one series of such fixed points. This can be accomplished by the arrangement shown in Figs. 4 and 5 wherein a shaft 41 is mounted on suitable supports 42 on a vehicle to rotatably support a drum assembly 43 having a series of radiation detectors R thereon, said detectors being arranged with their principal axes of sensitivity substantially radial of the drum. A worm gear 44 and

a worm 45 are suitably connected to an air motor 46 (Fig. 5) or other means for synchronized operation with the forward movement of the supporting vehicle.

The leads from each radiation detector are brought radially inward of the drum assembly and connected to contacts 47 and 48, the latter being positioned to connect with commutator segments 49 and 51 connected in turn by leads 52 and 53 to suitable amplifying and recording devices. It will be noted that except in the lower arc of drum travel as viewed in Fig. 5, the radiation detectors are disconnected from the associated amplifying and recording apparatus and are not connected therewith until each enters upon its measuring cycle. The assembly as viewed in Fig. 5 rotates in a clockwise direction with the vehicle traveling from left to right, each radiation detector becoming connected with commutator segments 49 and 51 as it enters its observing cycle. As shown in Fig. 4, any desired number of detectors may be employed in each series. With the arrangement shown, readings can be taken upon a number of different fixed points O, the readings being recorded for subsequent analysis.

While all the detectors in Fig. 4 are shown connected to a single recorder, it is to be understood that each of the detectors or each series thereof may be connected to individual amplifiers and recorders, the separate connections being made through additional commutator segments 49 and 51 or like means.

A series of lugs 54 are mounted on the drum assembly, one of such lugs being positioned adjacent the base of each series of detectors. On rotation of the drum assembly in clockwise direction as viewed in Fig. 5, the lugs contact an arm 55 connected to a switch 56 and operate solenoids 57 and 58, solenoid 58 being held in position by a delay device such as a dashpot until solenoid 57 has operated. Alternatively separate switches 56 with separate arms 55 can be provided for each solenoid, the switches being spread apart so that they are operated in sequence. Solenoid 57 is connected to a gate 59 of a magazine 61 and solenoid 58 is connected to operate a gate 62 of the same magazine. The magazine is filled with suitable marking devices 63. Thus as each detector assembly comes into detecting position and is connected to its associated amplifier and recording device through commutator segments 49 and 51, lugs 54 contact switch arm 55 to operate gates 59 and 62 in sequence and discharge a single marker on to the point or section being observed, the chamber between the two gates being reloaded.

Fig. 6 illustrates a modified arrangement of detectors wherein each series of detectors is arranged in lines non-parallel of the axis of the drum assembly. This arrangement permits readings of staggered fixed points.

The invention is particularly useful in the radioactive exploration of large areas at a relatively rapid rate. In so exploring either the continuous or the intermittent method of observation can be used. Assuming that a helicopter is used, the latter is moved over the area on a series of flights substantially parallel to one another and spaced approximately the same distance apart. Readings are taken and recorded during the flights. If the readings be of the continuous type, markers are dropped at regular intervals, the positions of each marker being identified with respect to the readings being taken. If the readings are recorded on a continuous tape as is the usual procedure, the recording device can be given an added pulse, by suitable electrical or mechanical means when each marker is dropped. When the intermittent observation method is used, the markers may be dropped at the beginning of each observation cycle as previously explained. In either case, each marking is correlated with a reading.

On completion of the survey after all readings have been taken and all the markers applied, the area may be photographed. By reason of the markers being visible on the aerial map thus made, the markers can be correlated immediately with the ground and the readings correlated with the markers. Thus a complete and accurate radioactive survey of the entire area can be quickly made. Obviously the map can be further refined by other modifications such as the drafting of isoradins thereon.

As alternative methods of recording the survey, the area being surveyed may be photographed continuously with a suitable recording camera mounted on the moving support or a recording camera, preferably with a telescopic lens, may be mounted in conjunction with the detector or detectors to move therewith so that the optical axis of the camera is substantially coincident with the principal axis of sensitivity of the detector assembly. The camera may be synchronized for operation when the detector assembly is at position B (Fig. 1) whereby a photographic record of the observed zone can be made simultaneous with the survey. In such case an annular type counter would be preferred, the annulus being fitted with a telescopic lens of a recording camera. Such a combination enables the making of a master log of radioactivity and a picture of the terrain at the same time.

Obviously many modifications and variations of the invention as above set forth may be made without departing from the spirit and scope thereof, and therefore only such limitations should be imposed as are indicated in the appended claims.

I claim:

1. A method of determining the radiation over an appreciable period of time from a predetermined section of an area being explored by a radiation detector mounted on a support moving relative to said section comprising the steps of directing said radiation detector on said section, maintaining said radiation detector directed on said section by movement of the principal axis of sensitivity of said radiation detector relative to said moving support, rendering said detector inoperative after a predetermined time of observation, returning said detector to its original position on said support for observation of a second section of the area, and rendering said detector operative for observation of said second section.

2. A method of determining the radiation over an appreciable period of time from a predetermined section of an area being explored by a radiation detector mounted on a support moving relative to said section comprising the steps of directing said radiation detector on said section, maintaining said detector so directed by movement of the principal axis of sensitivity of said detector relative to said moving support, and identifying the section so observed for subsequent correlation with the observed radiation.

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3. A relatively rapid method of prospecting a relatively large area for mineral and other earth deposits comprising the steps of measuring the radioactivity of each of a series of spaced points on the area being explored, recording the measurements, marking the points so measured, correlating the marked points with the area being explored, and correlating the measurements with the points to determine anomalies in the area.

4. A method of rapidly prospecting a relatively large area for mineral and other earth deposits by substantially continuous movement thereover at a relatively high speed comprising the steps of measuring the radio-activity of a series of spaced points in the path of movement, recording the measurements, marking the points so measured, recording the points so marked on a representation of the area, and correlating the measurements with the points to determine anomalies in the area.

5. An improvement in prospecting apparatus for measuring radiation in an area to be prospected wherein a radiation detector support mounting a radiation detector is arranged to be substantially continuously moved over said area during the prospecting comprising means to pivotally mount said detector on said support, and means to swing the detector about the pivot in a direction opposite to the movement of the support and at a rate so proportioned to the speed of the support as to enable the detector to be maintained in detecting position with respect to a predetermined and fixed section of the area being prospected for an appreciable time interval and returning the detector to its initial position at the end of said time interval for observation of a second predetermined section, amplifying means for use with said detector, and means to maintain said detector connected to said amplifying means during its observing movement and to disconnect said detector from said amplifying means during its return movement.

6. An improvement in prospecting apparatus for measuring radiation in an area to be prospected wherein a radiation detector support mounting a radiation detector is arranged to be substantially continuously moved over said area during the prospecting, comprising a detector assembly including a plurality of detectors substantially radially disposed about an axis intended to be positioned generally parallel to the surface of the earth during prospecting, and means to revolve said detectors about said axis during the prospecting and at a rate such that during their exposure to the earth's surface, each is directed onto a fixed point on said surface for an appreciable interval of time.

7. The apparatus of claim 6 wherein said detectors are arranged in lines substantially parallel to said axis.

8. The apparatus of claim 6 wherein said detectors are arranged in lines non-parallel to said axis.

9. The apparatus of claim 6 including amplifiers and means to effect the connection of each detector and said amplifiers wnen said detector is in observing position relative to the surface of the earth and to disconnect said detector when not in said observing position.

10. The apparatus of claim 6 wherein means is provided in synchronism with said detectors to identify the fixed sections being observed.

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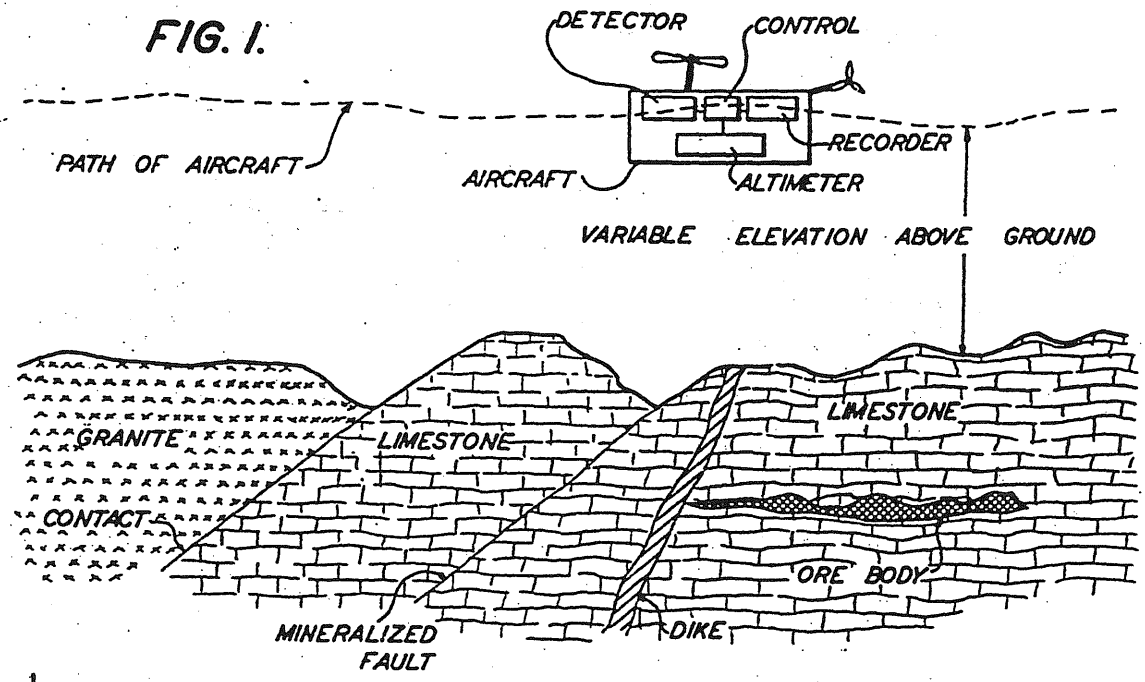
PROSPECTING USING GAMMA RAY DETECTION

Filed March 9, 1948 2 SHEETS—SHEET 1

FIG. 1.



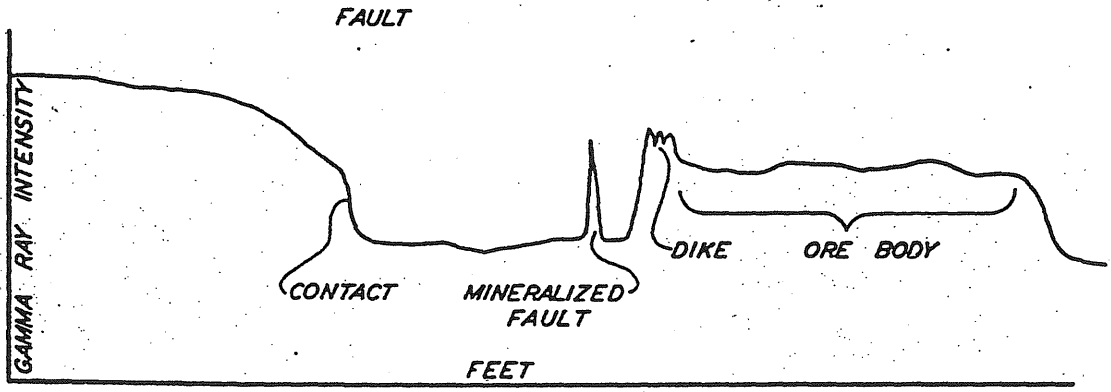
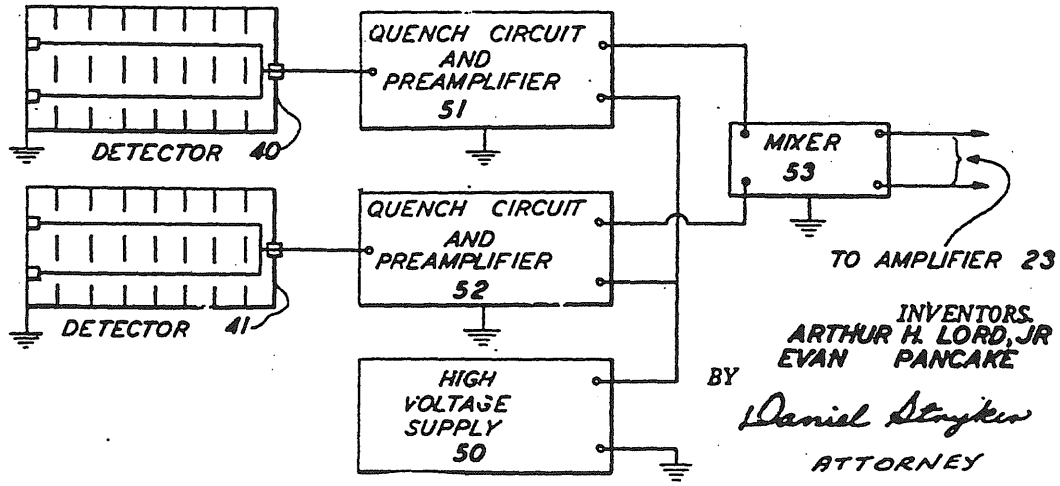


FIG. 4.



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Nov. 11, 1952 A. H. LORD, JR., ET AL 2,617,945

PROSPECTING USING GAMMA RAY DETECTION

Filed March 9, 1948 2 SHEETS—SHEET 2

FIG. 2.

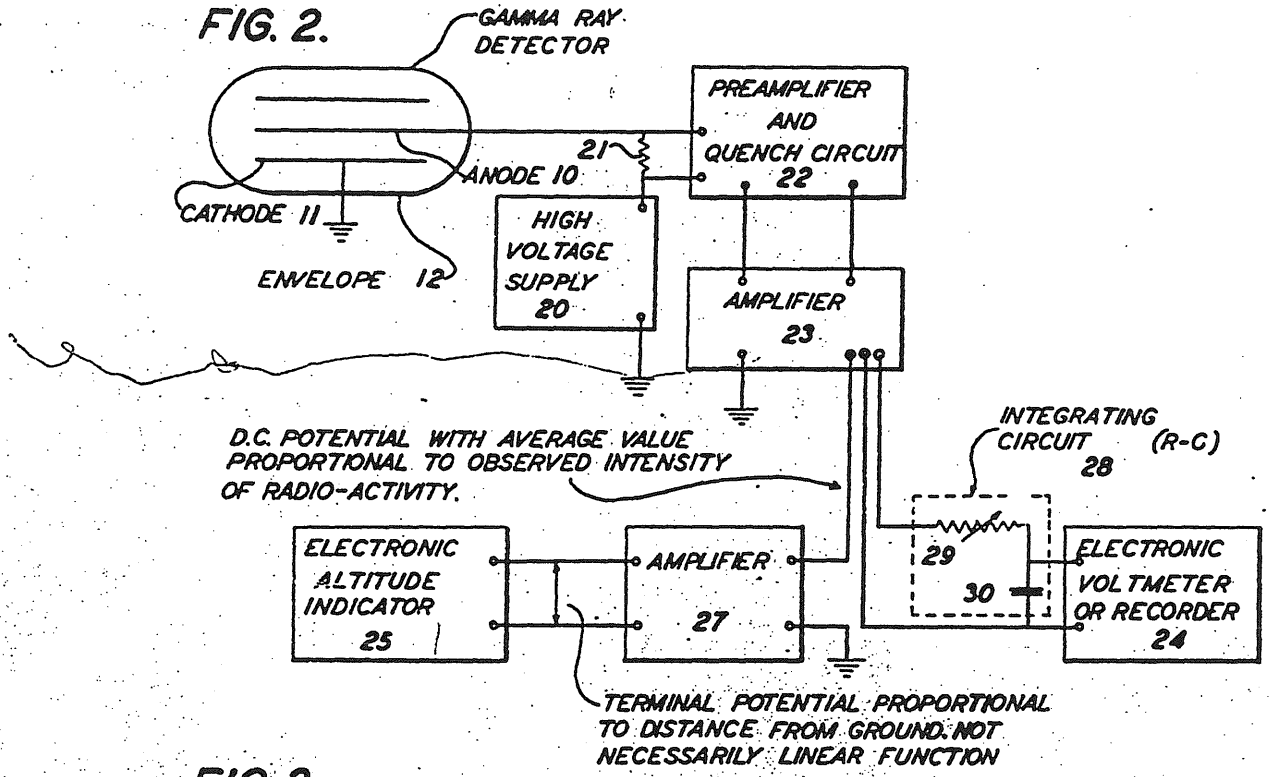
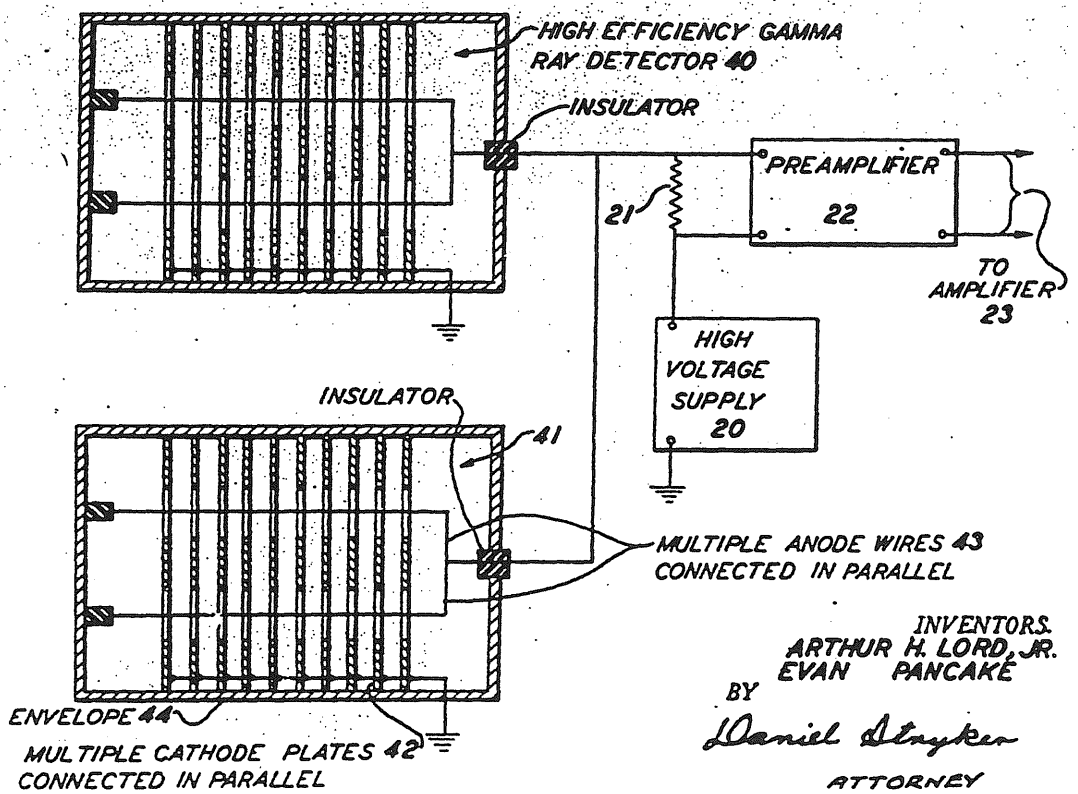


FIG. 3.



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2,617,945

PROSPECTING USING GAMMA RAY DETECTION

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Application March 9, 1948, Serial No. 13,844

3 Claims. (Cl. 250—83.6)

1

This invention is concerned with geophysical prospecting and particularly with geophysical surveys involving the detection of variations in the intensity of gamma rays emanating respectively from different points or zones along a traverse on an earth surface. The invention provides improvements in methods and apparatus for this purpose and is particularly useful in geophysical surveys employing airborne gamma ray detectors.

As disclosed in co-pending application Serial No. 13,842, filed March 9, 1948, it is possible to discover radioactive anomalies indicative of the presence of ore bodies and geological features such as faults, contacts, intrusions, etc, with gamma ray detectors of high efficiency. Thus it has been discovered that ore bodies which are so deeply buried that gamma radiation, if any, originating in the ore body is substantially completely absorbed by the overburden, may still be discovered by measuring differences in the intensity of gamma radiation originating close to the surface in the overburden itself. In other words, the presence of an ore body which is in itself not substantially radioactive (or if radioactive is so deeply buried that radiation originating in the ore body is so completely absorbed by the overburden that it does not serve to reveal the ore body) may still be detected by faintly radioactive "auras" in the barren overburden. Moreover, the differences in intensity which are noted when passing from one geological formation to another across a fault or contact are of great aid in geological mapping.

Given a detector of adequate size and efficiency, significant differences in gamma ray intensities along a traverse on the earth's surface may be detected even though the detector is several hundred feet in the air above the surface and is carried along the traverse at high velocity. Consequently, large scale geophysical surveys can be made rapidly and efficiently with airborne instruments, for example, a high efficiency gamma ray detector carried in a helicopter.

In carrying out such a survey it is desirable that the detector be flown along the traverse while maintaining a constant elevation above ground, for variations in this elevation cause changes in observed intensity. However, gamma radiation surveys of the type under consideration find much application in prospecting for deposits of metallic minerals, for example, ore bodies of copper, lead, iron, etc., and these generally occur in mountainous terrain—where the relief is such that it is difficult to fly a traverse maintaining

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even approximately a constant elevation above ground. Even in relatively flat terrain such an operation is not easy. If the elevations of the instrument and of the surface along the course of the traverse are known, it is, of course, possible to correct the observed intensities for the differences of elevation above ground. Such an expedient however, is tedious and may require extensive topographical mapping since a surface profile must be run along each traverse and the elevation of the instrument for each reading must be determined.

In accordance with the instant invention, the foregoing difficulties are eliminated by automatically correcting the observed gamma ray intensities for changes in elevation of the detector. Thus the invention contemplates apparatus for measuring gamma radiation from the earth which comprises a gamma ray detector, an indicator for registering the intensity of the detected gamma rays, an altimeter, and means for automatically varying the response of the indicator to the detector with changes in elevation detected by the altimeter. The entire combination may be, and preferably is, mounted in an aircraft, which may be considered as cooperating with the combination in producing the result, since it carries the detector and associated apparatus rapidly along the traverse being surveyed.

The altimeter employed may be of various types. In relatively flat terrain an aneroid barometer is useful as the governor for the automatic compensation means. However, in areas of high relief an electronic altimeter, say one of the echo ranging type, is almost essential and is desirable even in flat country. Such an altimeter, instead of detecting elevation above sea level or some other datum plane, detects the absolute distance between the airborne detector and the ground, and may permit more accurate compensation for loss of intensity of gamma radiation in this distance.

These and other aspects of the invention will be more thoroughly understood in the light of the following detailed description, taken in conjunction with the accompanying drawings in which:

Fig. 1 is a diagram illustrating a survey conducted in accordance with the invention employing an airborne detector with an automatic compensator which governs the registered gamma ray intensity;

Fig. 2 is a block diagram of apparatus for the practice of the invention;

Fig. 3 is a diagram illustrating a modification of the apparatus of Fig. 2 with a conventional Geiger-Mueller detector replaced by a battery of high efficiency plate-type detectors; and

Fig. 4 is a wiring diagram illustrating a further and preferred arrangement for employing a battery of high efficiency detectors.

Referring to Fig 1, an aircraft, say a helicopter, is shown flying along a traverse at varying elevation, both with respect to a level datum plane and the earth's surface. A vertical plane drawn through the traverse shows a partial geological section. Thus the aircraft, in flying from right to left at varying elevation approximating 200 feet, first passes over a flat lying ore body, say a lense of galena in limestone. Next in the traverse is a dike of igneous rock, say andesite, which penetrates the limestone and outcrops. This is followed by a mineralized fault in the limestone, the rock on both sides of the fault being the same, and then a contact between limestone and granite.

The gamma ray intensity, referred to a plane at constant elevation above the ground, is measured by equipment carried in the aircraft. The equipment consists of a gamma ray detector, preferably one of high efficiency and large size, a recorder for the intensity of the gamma radiation detected, an altimeter, and a control circuit interconnected between the detector, the recorder and the altimeter. The altimeter determines the vertical distance of the detector above the ground level, and preferably is of the electronic echo-ranging type which produces an output potential which varies as the distance above ground. The control circuit may be of the types used for automatic volume control in radio receivers and is designed to vary the amplitude of the intensity registered by the recorder to compensate for changes in elevation above ground. Thus, as the distance changes the amplitude is automatically corrected.

Below the geological section in Fig. 1 is a graph of recorded intensity along the section. Beginning at the right, the gamma ray intensity, adjusted for altitude, is relatively low, since in general gamma radiation from unmetamorphosed limestone is slight. However, in the neighborhood of the ore body the limestone is considerably more radioactive, even though barren of ore, and the recorded gamma ray intensity is higher. In other words, the detector responds to a radioactive aura in the overburden and shows a higher gamma ray intensity. The cause of such auras is not thoroughly understood, and they may be due to the introduction into the overburden of infinitesimal amounts of radioactive minerals at the time the ore body was formed or to the later introduction of radon, thoron, or actinon in gaseous state or dissolved in water. Whatever the reason, such faintly radioactive auras are distinguishable with proper apparatus in a number of cases involving a variety of country rocks (both sedimentary and igneous) and a variety of ore-forming processes including magmatic intrusion, replacement, alteration, etc.

The presence of the acid igneous dike is shown by a sharp increase in intensity which falls off again in the unaltered limestone to the left of the dike but increases sharply as the mineralized fault is crossed. The fault is thus revealed by a positive anomaly, although on occasion mineralized faults exhibit less radio-activity than the rocks on either side and so give rise to a negative anomaly.

As the surface exposure of the contact is passed, there is a sharp increase in recorded gamma ray intensity, indicating that the granite is more radioactive than the limestone, and the observed intensity increases toward the left as the detector becomes more influenced by the underlying granite.

A geologist, following along the traverse on the ground (say from left to right) and knowing the gamma ray intensities recorded as described above in an airborne survey, will recognize the contact between the granite and limestone, the mineralized fault in the limestone, and the outcrop of the acid dike. To the right of the dike, the high positive anomaly in the limestone will suggest the presence of an ore body, say an intruded lense generated by the dike or a replacement deposit. In any event the anomaly will warrant additional investigation, perhaps by more detailed gamma ray intensity surveys conducted on the ground, followed by core drilling or other type of exploratory excavation.

Were it not for the compensation of gamma ray intensity for altitude, variations in this factor might produce apparent anomalies which would be false and misleading.

A clear understanding of the instrumentation involved in the practice of the invention will be gained from Fig. 2. The apparatus there illustrated comprises a gamma ray detector. This is shown, for purposes of simplicity, as a conventional Gieger-Mueller counter provided with an anode wire 10 concentrically disposed in a metallic cathode tube 11, the two being enclosed in an envelope 12 of glass or the like, filled with an ionizable gas, say a mixture of alcohol and argon, at reduced pressure. Such a detector, if it is sufficiently large and efficient, may detect significant differences in gamma ray intensity at suostantial elevation above the ground in which the gamma rays originate. However, because of the relatively low efficiency of conventional Geiger-Mueller counters, which seldom exceeds ½% (only one ray out of 200 entering the active volume of the counter being detected) and because variations in "background" due to cosmic rays, etc., may obscure minor but significant differences in gamma ray intensities, we prefer to employ devices having high active volume or high efficiency and preferably both.

Generally speaking, the bigger the active volume of the detection equipment employed, the greater will be the counting rate. This large active volume may be obtained with a single counter, or with a number connected in parallel (as in Fig. 3), but preferably is obtained with a battery of detectors arranged as shown in Fig. 4 and described later in this specification.

Various types of detectors may be employed, including conventional Geiger-Mueller counters and those of the crystal and ionization chamber varieties. However, for airborne surveys, where the significant differences in intensities may be very small, a detector of high efficiency for gamma rays—say 5% or more—should be employed. One such type of detector is disclosed and claimed in U. S. Patent No. 2,397,071, granted March 19, 1946. It is illustrated diagrammatically in Figs. 3 and 4 which will be described later.

To return to Fig. 2, the conventional Geiger-Mueller counter there illustrated is connected across a D. C. high voltage supply 20 through a resistance 21 and ground, say the frame of the aircraft or other good conductor. Normally the potential difference between the anode and the cathode is nearly, but not quite, high enough to

cause an electrical discharge to take place. If an ionizing ray enters the active volume of the detector the gas filling may be ionized with resulting discharge, causing a current flow of the order of a few microamperes and a large voltage drop across the resistance. The discharge will cease after a short time, due to the self-quenching characteristics of the gas filling, which may be aided by a special quench circuit, for example, that described on pages 42–43 of "Radioactivity and Nuclear Physics" by Cork (Van Nostrand, 1947).

An electronic preamplifier 22 is connected across the resistance of Fig. 2 and if desired, a quench circuit may be incorporated in this preamplifier. The output of this preamplifier is sent to a main amplifier 23 (equipped with a conventional automatic volume control circuit as noted in connection with Fig. 1) where the sudden voltage drop across the resistance is further amplified, and the compensated output of this latter amplifier is introduced into an electronic voltmeter or recorder 24 which indicates gamma ray intensity. An electronic altitude indicator 25 of the echo-ranging type is employed to regulate recorded intensity. It has an output potential which varies in proportion to the distance of the indicator above ground, although this is not necessarily a linear function.

For compensation purposes, a potential is required which varies inversely as the effect of altitude on gamma ray intensity at detector height. This is obtained by feeding the output of the altitude indicator or measurer into an amplifier 27 which has the necessary characteristics and whose output potential varies as required above.

The output of the amplifier 27 is connected to the automatic volume control circuit of the amplifier 23, the return being through ground. The control circuit, as indicated in the discussion of Fig. 1, is designed to vary the amplitude of the intensity registered by the recorder to compensate for changes in elevation above ground.

An integrating circuit 28 consisting of a variable resistance 29 coupled with a condenser 30 is connected between the amplifier 23 and the recorder 24.

The resistance 29 is variable, and by adjusting it, the time constant of the integrating circuit may be varied, i. e. it may be made to average potentials over a longer or shorter period.

Other factors being equal, the observed intensity decreases as the distance of the detector above ground is increased. However, the electronic altitude indicator is carried with the detector at approximately the same elevation, its output potential being proportional to a function of the distance above ground. This potential feeds the second amplifier 27. If this second amplifier is properly designed and adjusted, substantially perfect compensation may achieved, with the result that the gamma ray intensity of the earth along the traverse being flown is shown by the voltmeter as if the detector were being flown at constant elevation above ground.

Although in a few cases pronounced anomalies in the intensity of gamma rays emanated along a traverse may be discovered with detectors of ordinary efficiency for gamma rays, practical operations require much higher efficiency, such as is obtainable with the detectors shown in Fig. 3. Referring to this figure, it will be seen that a plurality of high efficiency gamma ray detectors 40, 41 are connected in parallel across the D. C. high voltage supply 20 (in place of the conventional detector of Fig. 2) through the resistance 21. The preamplifier 22 is connected across the resistance as in Fig. 2, the balance of the apparatus, save for the detectors, being as indicated in this latter figure.

Each detector comprises a stack of circular metal plates 42 spaced from each other along the common axis of the plates. The cathode plates are connected in parallel with each other to ground. The cathode plates are perforated to provide free paths for a plurality of anode wires 43 that run perpendicularly through the plates and are connected in parallel to the high voltage supply through the resistance 21. Anodes and cathodes are enclosed in envelopes 44, which are gas-tight brass cylinders, filled with argon and ammonia at a pressure that is slightly sub-atmospheric.

The operation of the apparatus of Fig. 3 is the same as that of Fig. 2 except that the efficiency of gamma ray detection (due to the special construction of the detectors) is higher.

The apparatus of Fig. 4 employs a plurality of multiple plate multiple wire type detectors 40, 41, as in the apparatus of Fig. 3. However, in order to obtain improved resolving power, these detectors are connected to the amplifier 23 in another fashion. A D. C. high voltage supply 50 is connected to the cathode of each detector in parallel thereto through ground and to the anodes of these detectors respectively through quench circuit—preamplifier combinations 51, 52. The preamplifier outputs in turn are sent to an electronic mixer circuit 53 (such for example, as those employed in seismic prospecting equipment) and the output of the mixer in turn is sent to the amplifier, the balance of the equipment being as illustrated in Fig. 1.

The circuit of Fig. 4 is preferred over that of Fig. 3 because it reduces the recovery time of the circuit following quenching by reducing the capacitances of the individual detector circuits and thus reducing the time required for the voltage on the anode to reach a value above threshold potential following discharge. This in turn increases the observed counting rate for a given intensity of radiation.

We claim:

1. In apparatus for measuring gamma radiation from the earth, the combination which comprises a plurality of pulse type detectors for gamma radiation disposed close together and each comprising at least one anode wire and a plurality of apertured cathodes through which the anode passes, the cathodes being connected in parallel with each other, an individual quench-circuit preamplifier for each detector, the input of said amplifier being connected to the anode of its detector, an electronic mixer circuit with the several preamplifier outputs connected to its input, a D. C. high voltage supply connected in parallel to the cathodes of the several detectors and in parallel to the several preamplifiers, an amplifier having its input connected to the output of the mixer, an electronic voltmeter connected to the output of the amplifier, automatic echo-ranging means for determining the height of the detectors above the earth's surface, means connected to said automatic echo-ranging means for automatically increasing the amplification of the amplifier and the response of the voltmeter as the distance determined by the echo-ranging means is increased and vice versa to compensate for the change of gamma ray intensity at the

location of the detectors due to the change in said height.

2. In an apparatus for measuring gamma radiation from the earth during a traverse over the earth's surface including a detector for gamma radiation, the combination which comprises an electronic amplifier having its input connected to the detector, an electronic voltmeter connected to the output of the amplifier, automatic means for determining the height of the detector above the earth's surface, and means connected to said automatic height-determining means for automatically increasing the amplification of the amplifier and the response of the voltmeter as the height determined by said height-determining means is increased during the course of the traverse, and vice versa, to compensate for the change in intensity of gamma rays at the location of the detector due to the change in the height of the detector above the earth's surface.

3. In an apparatus for measuring gamma radiation from the earth in the course of a traverse of the earth's surface, the combination which comprises a detector for gamma radiation, an amplifying means connected to the output of the detector, indicating means connected to the output

of the amplifying means, automatic means for determining the distance of said detector from the earth's surface during the traverse thereof, and means connecting said automatic distance-determining means to said amplifying means for automatically increasing the amplification of said amplifying means and the response of the indicating means as the distance determined by the distance-determining means during the course of the survey is increased, and vice versa, to compensate for the change in intensity of the gamma rays at the location of the detector due to the change in the distance of the detector from the earth's surface.

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Number	Name	Date
2,404,250	Rajchman	July 16, 1946
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Oct. 20, 1953 G. HERZOG 2,656,470

PROSPECTING

Original Filed March 9, 1948 8 Sheets-Sheet 1

FIG. 1.

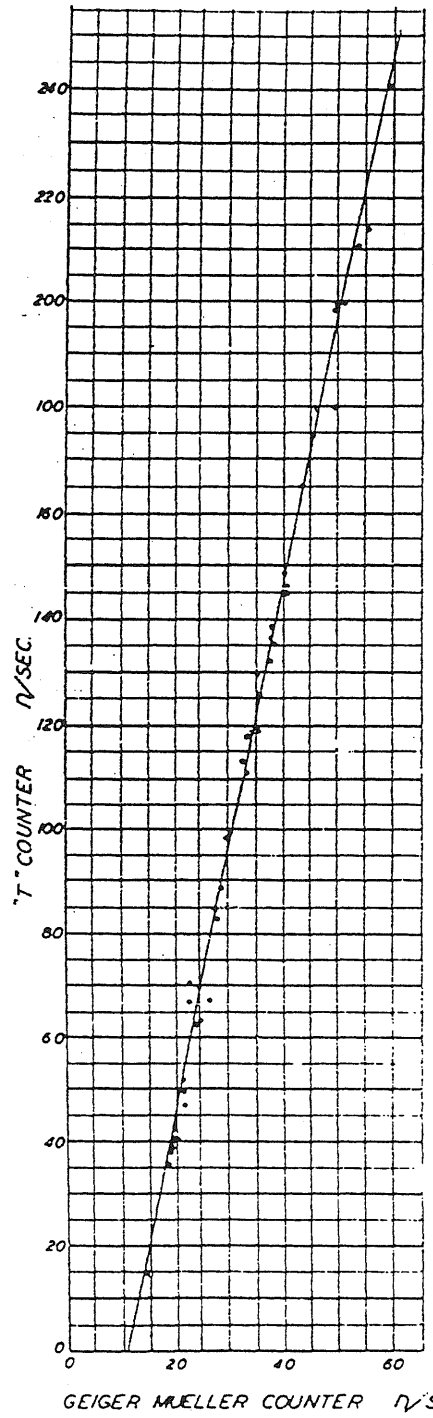
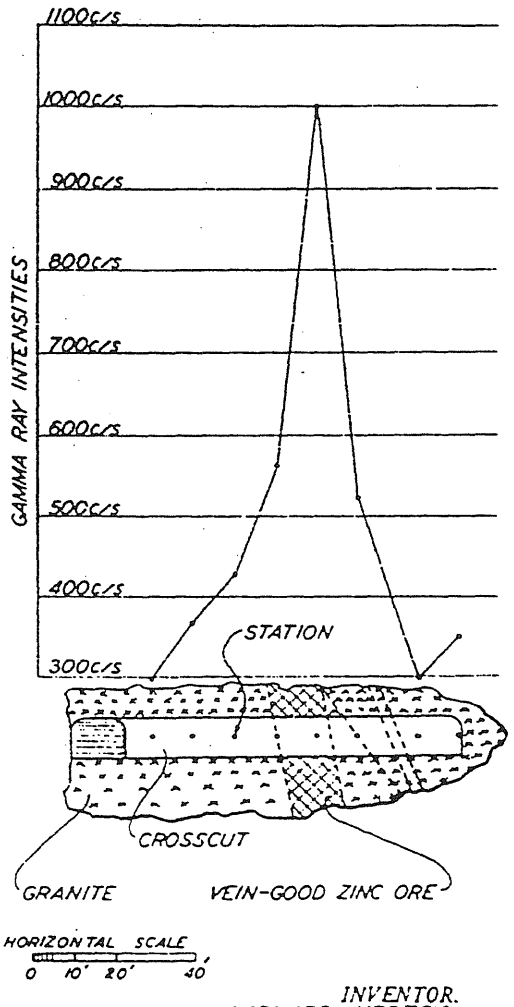


FIG. 7.



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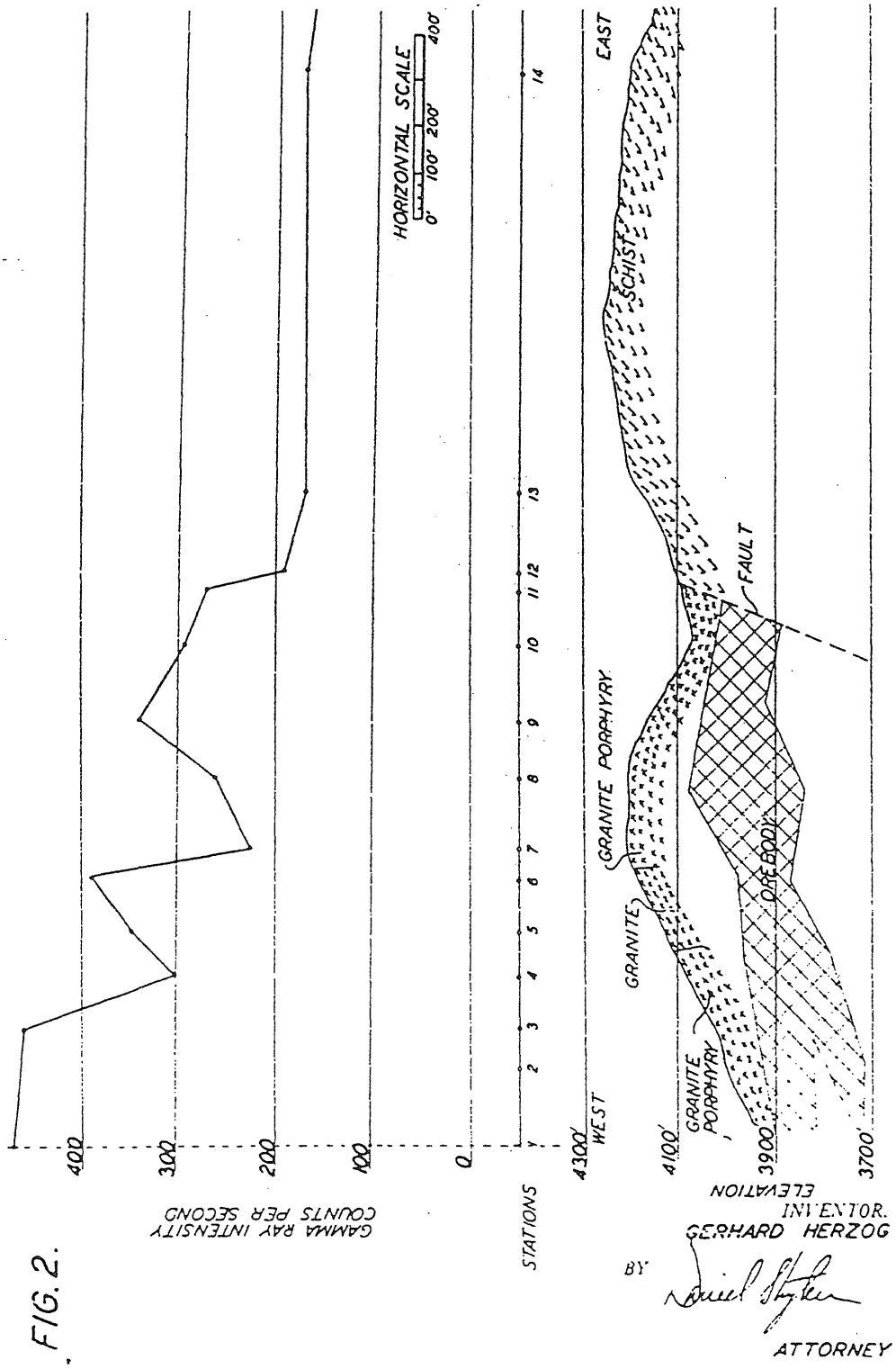

FIG. 2.

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PROSPECTING

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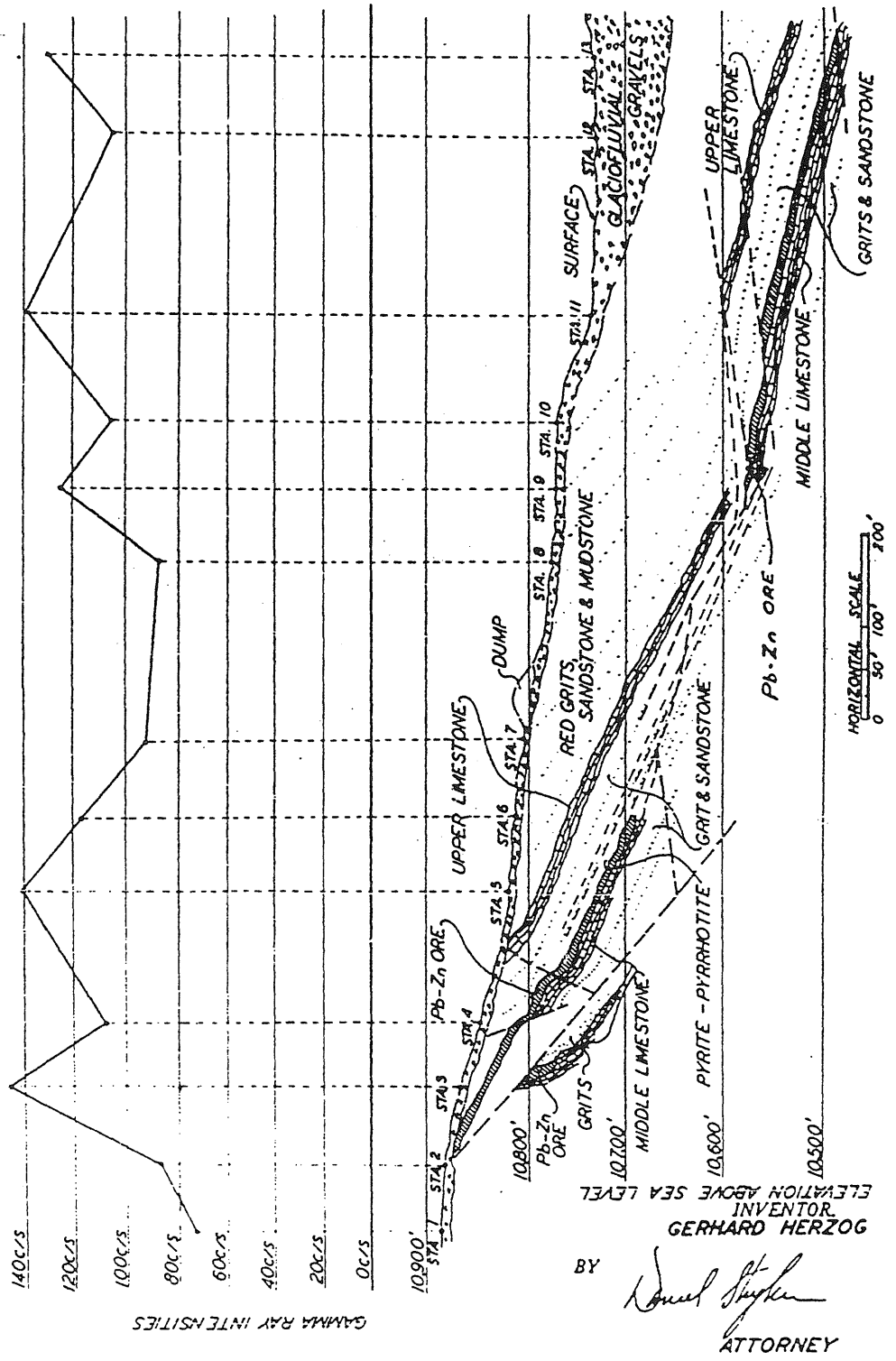

FIG. 3.

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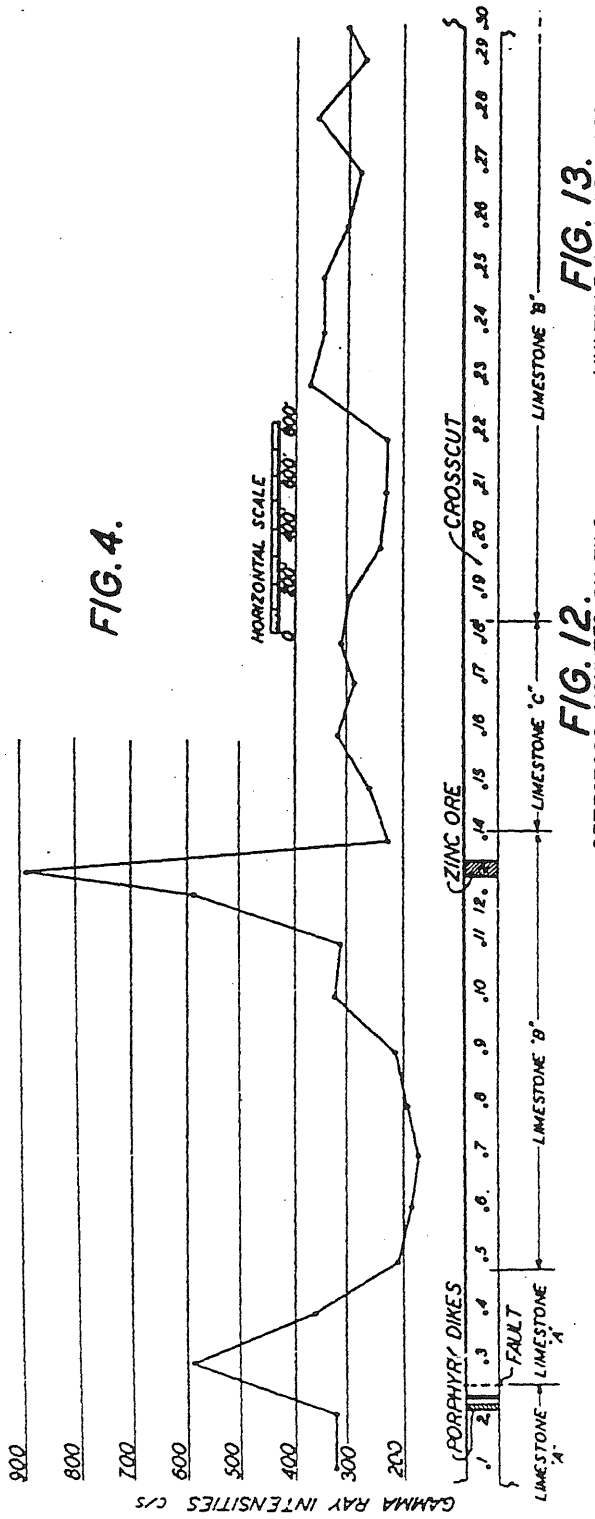

FIG. 4.

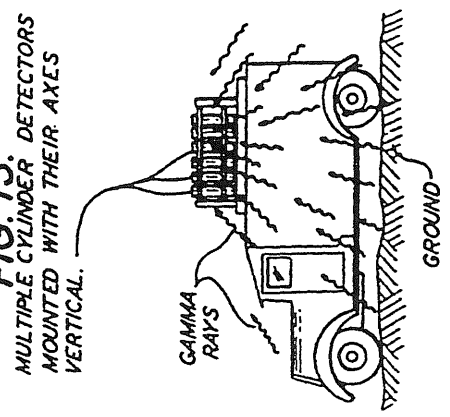

FIG. 13.
MULTIPLE CYLINDER DETECTORS MOUNTED WITH THEIR AXES VERTICAL.

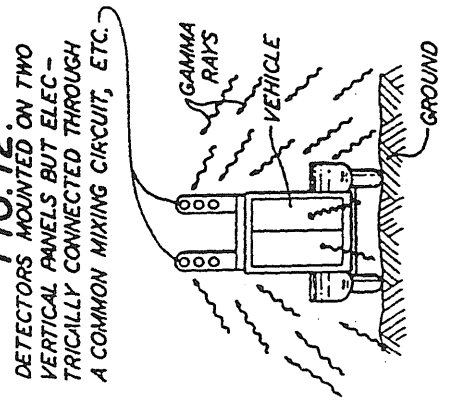

FIG. 12.
DETECTORS MOUNTED ON TWO VERTICAL PANELS BUT ELECTRICALLY CONNECTED THROUGH A COMMON MIXING CIRCUIT, ETC.

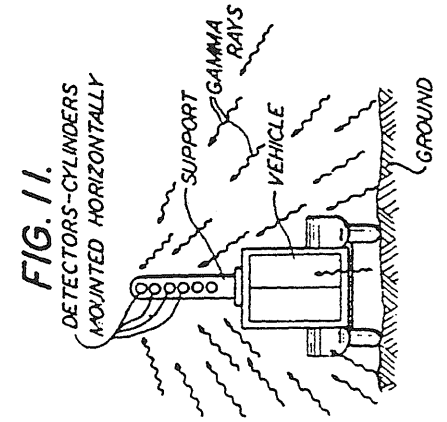

FIG. 11.
DETECTORS-CYLINDERS MOUNTED HORIZONTALLY

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FIG. 5.

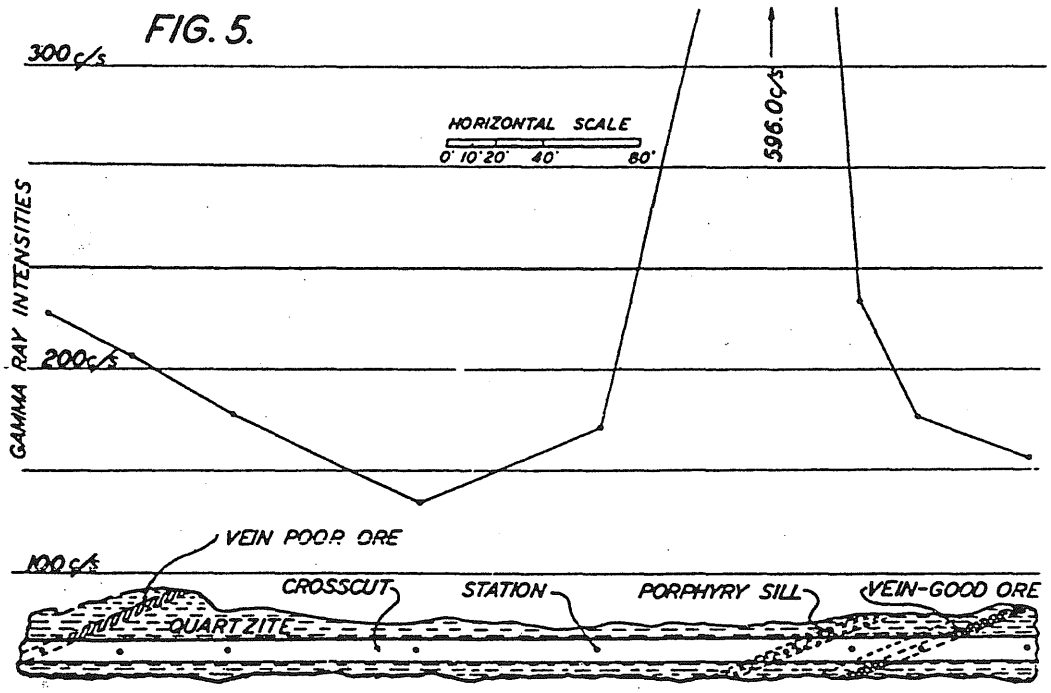
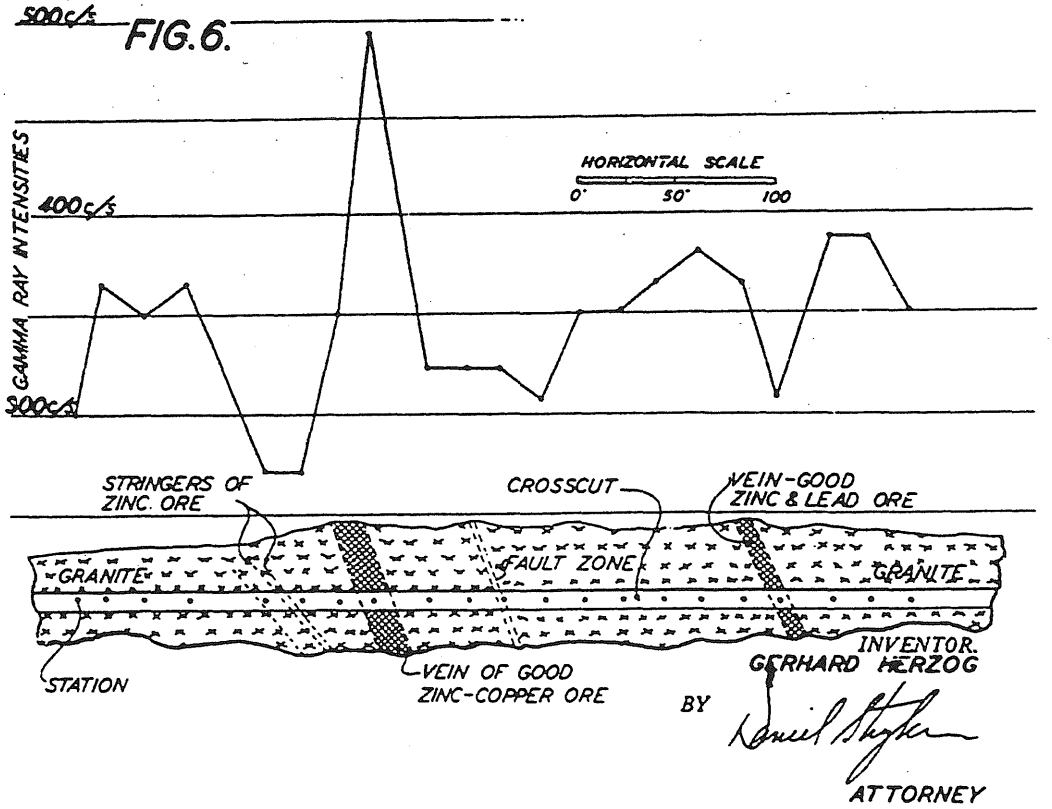


FIG. 6.



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PROSPECTING

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FIG. 8.

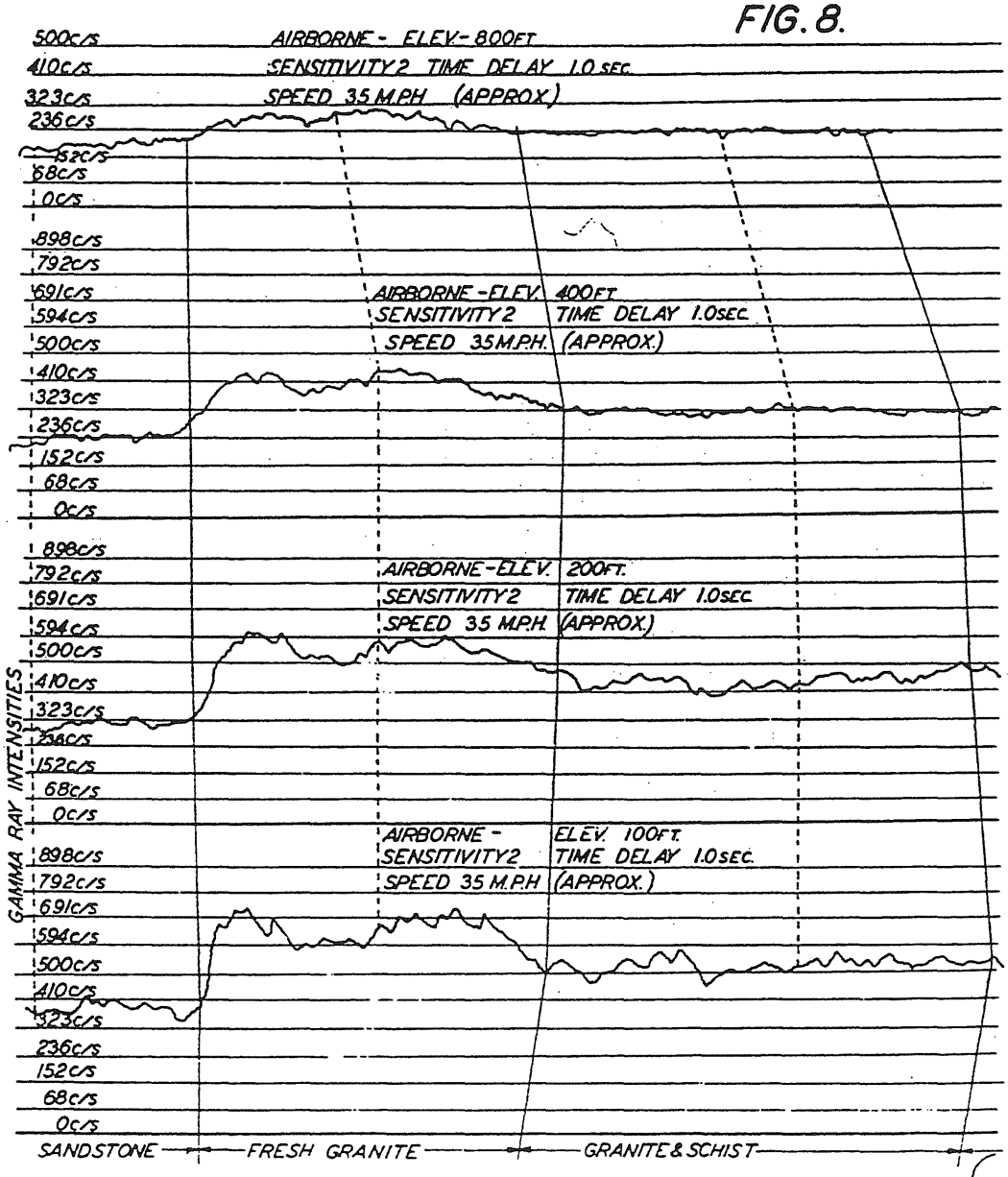

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FIG. 9.

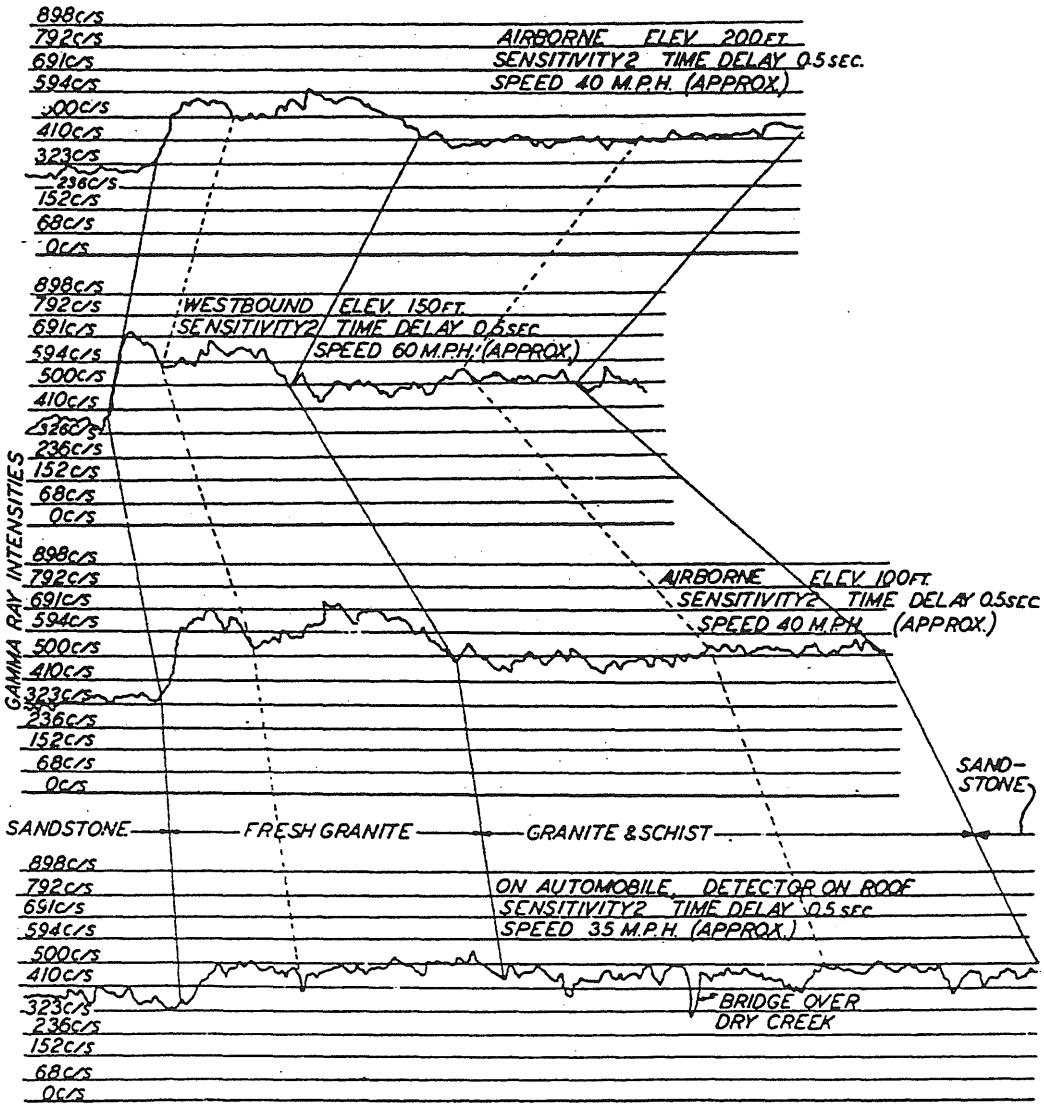

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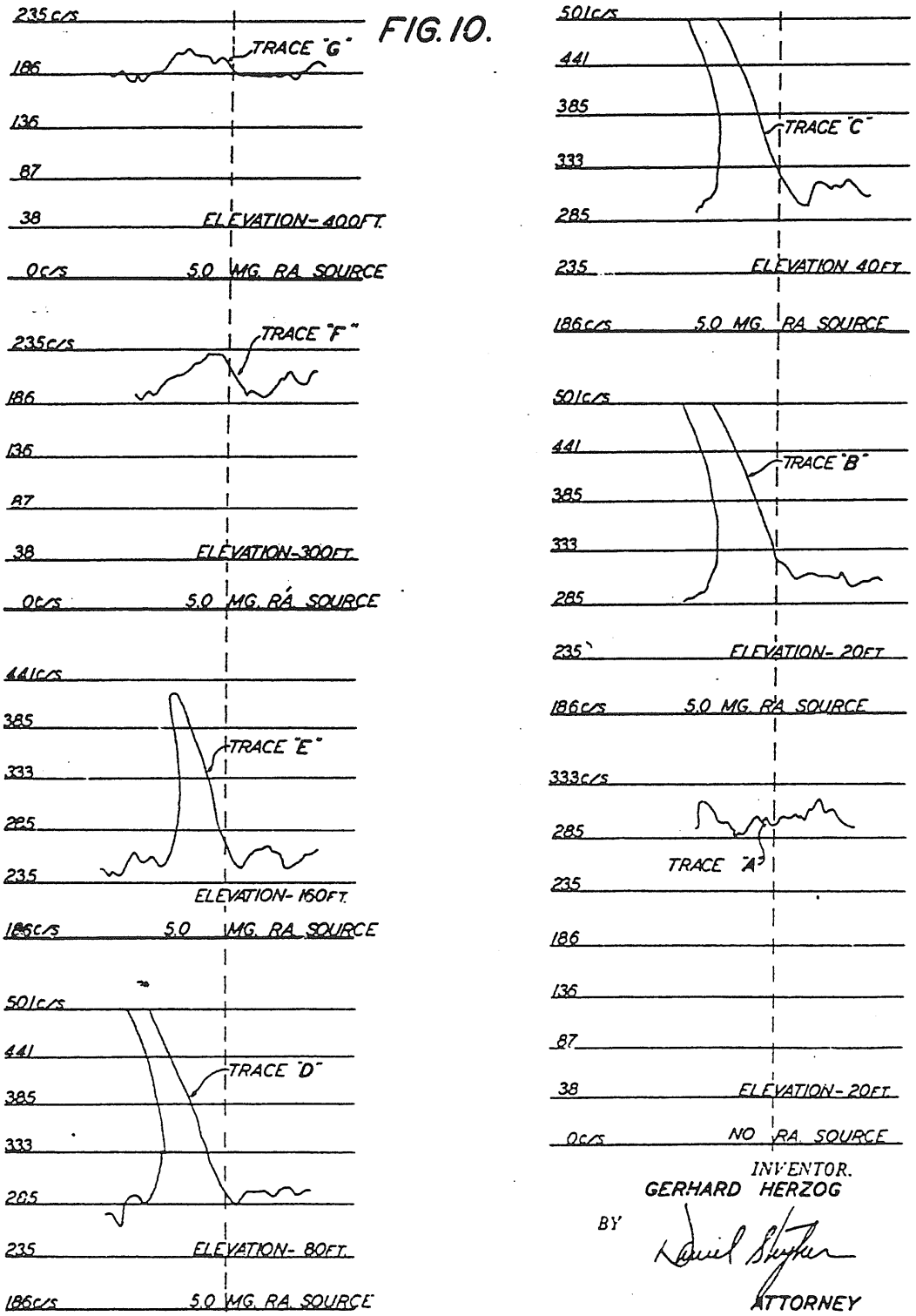
FIG. 10.



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2,656,470

PROSPECTING

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Original application March 9, 1948, Serial No. 13,842, now Patent No. 2,562,914, dated August 7, 1951. Divided and this application March 19, 1951, Serial No. 216,444

7 Claims. (Cl. 250—71)

1

This invention is concerned with prospecting for mineral deposits, particularly metallic mineral deposits, as distinguished from deposits of hydrocarbons such as oil and gas. Although it employs radiation detection, it is especially useful for the discovery and delineation of ore bodies of metals which themselves are substantially non-radioactive. In one aspect, it is useful for surface surveys, both along the ground and airborne, for the discovery and location of geologic features such as faults, contacts, intrusions, etc.

This is a division of my co-pending application Serial No. 13,842, filed March 9, 1948 (now Patent No. 2,562,914, granted August 7, 1951).

Radiation detection has been employed heretofore as a method for distinguishing between different rocks and rock strata, a well known example being the method of gamma ray logging in which a radiation detector such as an ionization chamber or a conventional Geiger-Mueller counter is passed along a bore hole, the counting rates corresponding to the different rock formations penetrated by the hole being observed.

Another practical example of the application of radiation detection in geophysics is the use of portable Geiger-Mueller counters which are moved along the surface of the ground while the counting rate is observed, the object being to discover deposits of strongly radioactive minerals such as those of uranium or radium. If such deposits outcrop or are buried under shallow cover, rays (particularly hard gamma rays) which emanate from the deposit may penetrate to the surface and register at the counter. The presence of such strongly radioactive deposits, if these are not too deeply buried, will thus be manifested by an increase in counting rate.

It is theoretically impracticable to locate buried ore deposits, even though these be highly radioactive, by surveys of radioactivity in the neighborhood of the deposits, except in those cases in which the overburden is so thin that it does not absorb the radiations from the ore deposit to the extent that significant variations in intensity of radiation due to the presence of the deposit are obscured. The naturally radioactive elements emit alpha, beta and gamma rays in various proportions and with different energies. The alpha and beta rays have very little penetrating power. The penetrating power of the gamma rays is higher; the absorption of these rays by any surrounding medium is governed by the exponential law. Assuming a reasonable absorption coefficient of 0.1 per cm. for the medium, say rock, a thickness of 23 centimeters will reduce the intensity of the hardest (i. e. most penetrating) gamma rays of thorium C by a factor of 10; 46 centimeters reduces the intensity by a factor of 100; 69 centimeters by a factor of 1000; 92 centimeters by a factor of 10,000; 115 centimeters by a factor of 100,000, etc.

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Practically all rocks are radioactive to some extent, and even with the most sensitive of available detectors, an overburden of a few meters reduces the intensity of the gamma radiation to the point where it becomes impossible to recognize the excess activity originating in the ore body over the "background" originating in the overburden. Nevertheless, I have discovered that it is possible to recognize and locate ore bodies through cover in excess of several meters by detecting variations in the intensity of gamma rays originating in the overburden itself, but relating indirectly to the ore body. Thus ore bodies may be revealed through detection of variations of gamma ray intensity at points so far removed from the ore body itself as to be, for all practical purposes, beyond the range at which significant differences of intensity of gamma rays originating in the ore body are detectable. In short, a gamma ray detector if it is sufficiently efficient and is employed for a sufficiently long time at each point where a measurement of gamma ray intensity is made, may be used to discover significant variations in the gamma ray emission at different points in the overburden which, indirectly, reveal the presence of the ore body.

The invention is not restricted to the discovery of ore bodies of the radioactive elements. In fact, it finds its major application in prospecting for ore bodies of non-radioactive metals including base metals such as iron, copper, lead, zinc, cadmium, tin, tungsten, etc., as well as precious metals such as gold, silver and platinum. The country rock or overburden in or under which such deposits occur generally gives significant deviations in gamma ray intensity from which the existence and location of the deposit may be determined. In other words, the deposits have faintly radioactive auras which, if properly detected, act as markers for the deposits, whether or not the deposits themselves are radioactive.

Barren country rocks, i. e. those in which there is no substantial content of commercial minerals, particularly the non-radioactive metallic minerals, are in general radioactive to some extent, and many show radioactivity equal to several micro-micrograms (10^{-12} gms.) of radium per gram of rock. It is the relatively slight differences in this radioactivity, particularly gamma

ray intensity, at spaced points in the general neighborhood of an ore body which indicate the presence of the latter. As indicated above, the determination of these differences in reasonable observation times and with the detectors of reasonable size, requires the use of detectors having a high gamma ray counting efficiency, several times the efficiency of the conventional Geiger-Mueller counter consisting of a tubular cathode around a wire anode. Such conventional counters have an efficiency of not to exceed about ½%: i. e. they detect on the average only one ray out of 200 received. At this low efficiency significant differences in gamma ray intensities may well be obscured. Gamma rays are emitted sporadically and at random and unless the observation time is long enough the count taken at any point may not be representative of the source. Moreover, even though the counting efficiency be increased or the time made long enough to counteract this tendency to error, significant differences may be obscured by accidental variations including those due to cosmic rays.

To state my discovery in another way, I have determined that it is entirely feasible to discover ore bodies by a method involving the detection of gamma radiation intensity, even though the bodies themselves are buried by overburden so thick that no practicably measurable amount of radiation emanating directly from the ore body penetrates to the surface at which the measurement is taken and even though the ore body be one which contains no material amount of radioactive minerals and would generally be classified as non-radioactive. The invention, in this aspect, is based upon my discovery that the substantially barren country rock or overburden which effectively prevents significant amounts of radiation emanating from the body from reaching the surface, in many cases manifests sufficient variations in gamma ray emissivity to act as a "marker" for the ore body. In other words, even though the ore body itself be substantially non-radioactive or if radioactive, so deeply buried that its emanated rays do not penetrate to the surface in significant amounts, gamma rays emanating from the barren ground (in which the ore body occurs) penetrate to the surface and will, by proper detection, yield an intensity pattern which reveals the ore body. In short, the invention contemplates the improvement in prospecting for deeply buried mineral deposits which comprises locating a related radioactivity anomaly at a remote earth surface by accurately determining the gamma ray intensities along said surface, the term "deeply buried" being employed herein to mean that the deposit is so far removed from the points at which the gamma ray intensity measurements are made that there is no significant variation in the measured intensities due to gamma rays emitted directly from the deposit.

In a series of investigations conducted in a number of mining districts throughout the western United States, including Butte, Montana; Bisbee and Miami, Arizona; Cripple Creek and Climax, Colorado; the Coeur d'Alene, Idaho; Grass Valley and Idria, California; and the Tintic and Bingham Canyon areas in Utah, it has been determined that useful gamma ray anomalies indicative of a variety of types of mineral deposits may be discovered through the practice of the invention. These anomalies have been found where the country rock in which the ore body occurs is igneous and also in cases in which the country rock is sedimentary. The reasons for the radioactivity of the country rock in the neighborhood of the ore body are not completely understood and may be various, depending upon the manner in which the ore body was formed and its subsequent alteration. The naturally radioactive elements include those of the uranium, thorium and actinium families and potassium. In some instances, radioactivity in the country rock adjacent to an ore body may be due to introduction of one or more of these elements at the time the ore body was formed, say by magmatic intrusion. In other cases, it may be due to radon, actinon, or thoron which penetrated the rock subsequently either in gaseous state or in solution in water. Whatever be the reasons, the radioactivity of the country rock and the variations in this radioactivity are sufficient to enable discovery and delineation of associated ore bodies in a great variety of cases.

Theoretically, perhaps, a gamma ray detector of any efficiency might be employed for the detection of deeply buried deposits through the detection of gamma ray anomalies originating in the overburden, provided that a sufficient time were allowed for each reading. With ordinary detectors however, this time is so long as to be completely impractical, and if less than the required time is taken, the readings will be without significance. As already noted, the conventional Geiger-Mueller counter consisting of a tubular cathode disposed around an anode wire has a detection efficiency for gamma rays of approximately ½%. At this efficiency, the time required for each observation becomes a matter of hours and even then the results may be vitiated by accidental variations. Consequently, from a practical standpoint, a detector having a considerably higher counting efficiency for gamma rays only, say a crystal type of detector should be employed.

Any type of gamma ray detector may be employed for the discovery of auras of mineral deposits through the practice of the invention, provided that the gamma ray intensities to be measured are sufficiently high and differ greatly from point to point along the traverse being prospected, and provided further that sufficient time is employed for each reading. In the majority of instances, however, the gamma ray intensities to be measured (and more especially the significant differences in gamma ray intensity to be determined) are small, so that special equipment is desirable.

Generally speaking, ionization chambers are less desirable than tube counters, for example Geiger-Mueller detectors, in the practice of the invention. In turn, conventional Geiger-Mueller counters are not as suitable as other types of detectors which have a higher counting efficiency for gamma rays and substantially the same efficiency for all other types of radiation. Thus the crystal type of detector (employing a diamond or some other gamma ray-sensitive crystal as a detecting element) or detectors of the type described and claimed in U. S. Patent No. 2,397,071, granted March 19, 1946 are presently preferred.

Since, in general, the gamma ray intensities to be measured are of a low order, counting rates tend to be small. The counting rates may be increased by employing a single Geiger-Mueller detector of large size, i. e. by increasing active counter volume, but counting rate as well as efficiency of detection may be increased by increasing cathode area in the Geiger-Mueller detector.

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for example, by employing a bundle of Geiger-Mueller detectors (preferably disposed in a single envelope as is disclosed, for example, in Patent No. 2,486,944, issued November 1, 1949, to D. G. C. Hare. Other factors being equal, it is better to employ a number of small Geiger-Mueller detectors connected in parallel than a single such detector of equivalent active volume, since in this way the advantages of increased cathode area and increased active volume are obtained.

As indicated above, a Geiger-Mueller detector consists essentially of a tubular cathode and a coaxial wire anode running through it. The two are enclosed in an envelope within which a suitable gaseous atmosphere (say a mixture of argon and alcohol) is maintained, usually at a subatmospheric pressure. Normally the potential difference between the cathode and the anode is nearly, but not quite, high enough to cause a discharge to take place. If an ionizing ray passes into the detector a discharge may take place with resultant current flow. The discharge ceases after a short period of time, after which the counter is again in condition to register or "count" ionizing rays.

For all except gamma radiation, the Geiger-Mueller counter is highly efficient. It will detect alpha and beta radiations and the penetrating particles of cosmic rays with substantially 100% efficiency. However, its efficiency for gamma radiation is low, say only ½% or on the average only one out of each 200 gamma rays entering its active volume triggers the counter. We have discovered that for the location in a surface survey of the faint differences in gamma ray intensities that are indicative of most deeply buried ore deposits, as well as most contacts, faults, and similar geologic features, the survey should be made with a detector which has a substantially higher efficiency for gamma rays than the conventional Geiger-Mueller detector (preferably at least 4 or 5 times) and substantially the same efficiency as the conventional Geiger-Muller counter for all other radiation. Ionization chambers do not serve this purpose, but crystal type detectors (which employ a crystal, such as a diamond that becomes momentarily conductive upon the entry of radiation and permits the passage of current), scintillation detectors employing a fluorescent screen of naphthalene to obtain scintillations which are measured by a photomultiplier tube and detectors of the multiple cathode plate type, as described and claimed in U. S. Patent No. 2,397,071, granted March 19, 1946, are well suited to the practice of this aspect of the invention. Thus my invention contemplates the conduct of a survey along or above the earth's surface by measuring the gamma ray intensities at a series of points on or above the surface with an efficiency substantially greater than that obtainable with a conventional Geiger-Mueller counter while simultaneously, measuring together with the gamma radiation intensity, the intensity of other radiation present but with substantially the same efficiency as that obtainable with the conventional Geiger-Mueller counter. In this way faint differences in gamma ray intensity which are indicative of geological features such as faults, contacts, mineralized zones, etc., may be detected with airborne instruments at elevations up to at least 800 feet above the earth while moving at high velocity.

A further explanation of the advantages of the employment in surface surveys, and especially surveys conducted at substantial elevation above the surface, of a detector having the characteristics described above is given hereinafter.

These and other aspects of the invention will be clearly understood in the light of the following detailed description, taken in conjunction with the accompanying drawings in which:

Fig. 1 is a graphical comparison of counting rates of a conventional Geiger-Mueller counter and a preferred counter for the practice of the invention;

Fig. 2 is a graphic representation of a surface survey made in accordance with the invention over a buried copper deposit of the massive disseminated type;

Fig. 3 is a similar representation of a surface survey made over a series of buried replacement type lead-zinc deposits;

Fig. 4 is a graph showing the results of a horizontal underground survey in a limestone cut by porphyry dikes and a zinc replacement type deposit;

Fig. 5 is a graph of the results of an underground survey along a cross-cut through porphyry sills and lead-zinc replacement deposits occurring in quartzite;

Fig. 6 shows the results of an underground survey through granite cut by a zinc-copper vein indicated by a positive anomaly and a zinc-lead vein indicated by a negative anomaly;

Fig. 7 illustrates a strong positive anomaly encountered in an underground survey across a zinc vein occurring in granite;

Fig. 8 gives a comparison of survey results with airborne equipment flown at various elevations across a granite plug occurring in sandstone;

Fig. 9 gives a comparison of survey results with equipment flown at various elevations and carried along the surface across the granite plug of Fig. 8;

Fig. 10 illustrates the effect of a radioactive survey marker employed to correlate survey results with terrain in airborne operations at various altitudes;

Fig. 11 is a diagram illustrating a preferred mounting arrangement for a battery of detectors employed in a surface survey with a vehicle or the like; and

Fig. 12 and 13 show modifications of the mounting arrangement of Fig. 11.

Substantially any radiation detector which is sensitive to gamma radiation will also detect alpha and beta radiation and other radiation such as the penetrating particles of cosmic radiation. In fact, detectors in general have a higher efficiency for other types of radiation than for gamma rays. In geophysical prospecting employing radiation detectors, the gamma radiation is detected along with other radiation, some of which originates in the detector itself because of contamination of the materials employed in the construction of the detector and some of which is cosmic radiation, which has components so penetrating that they are encountered in mines, etc., several thousand feet below the surface. Hereinafter, the detected radiation other than gamma radiation is referred to as "background," and this background because it is emitted sporadically and at random and also because of its relatively high intensity may well obscure significant variations in gamma ray intensities between different points along a traverse and under the most favorable conditions reduces the contrast between readings obtained

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at different points. I have discovered that with certain types of radiation detectors the efficiency for detection of "background" does not increase proportionally to the increased efficiency of the detector for gamma rays, with the result that as the detection efficiency for gamma rays is increased, a greater contrast between readings is obtained and there is less chance that small but significant variations in gamma ray intensity from point to point along or over the earth's surface will be vitiated by variations in background, particularly cosmic rays. As already indicated, two of these certain types of radiation detectors are the crystal type and the type employing a multiplicity of cathode plates disposed transverse to one or more anode wires which pass through apertures in the plates. The virtues of a detector of this type over a conventional Geiger-Mueller counter have been demonstrated in comparative tests. The results of these tests are illustrated in Fig. 1, which is a plot of counting rates obtained with a conventional Geiger-Mueller counter at a series of points along traverses on the earth's surface against the counting rates obtained at the same points with a multiple plate type of counter having 12% less active volume due to minor differences in length and diameter. The observed counting rates of the multiple plate type of counter (hereinafter called the T counter) are plotted as ordinates against the counting rates with the Geiger-Mueller counter plotted as abscissa.

All the points fit very closely to a straight line relation. The straight line, which is shown in Fig. 1, was calculated with the method of least squares. If T and G are the counting rates per second for the T counter and for the Geiger-Mueller counter respectively the equation for the straight line is:

$$T=4.945(G-10.843) \tag{1}$$

Theoretically one should expect a relationship between T and G according to Equation 2.

$$T-t=K(G-g) \tag{2}$$

where t and g are the constant background rates for the T counter and the Geiger-Mueller counter, respectively. The difference T minus t on the left side of the equation is then the counting rate due to the gamma rays from the ground alone. Similarly the difference G minus g is the counting rate due to gamma rays alone for the Geiger-Mueller counter. Equation 2 expresses that the gamma ray count for the T counter is a multiple of the count for the Geiger-Mueller counter. Accordingly K is the relative efficiency to gamma rays of the T counter as compared to the Geiger-Mueller counter. Equation 2 can be rewritten in the form of Equation 3.

$$T=K\left[G-\left(g-\frac{t}{K}\right)\right] \tag{3}$$

The experimental relation as expressed in Equation 1 has the same form as has Equation 3 and by comparison it appears that the relative efficiency of the T counter compared to the Geiger-Mueller counter is 4.945. The difference g minus t divided by K must be equal to 10.843. By substituting the letter C for the value 10.843 in Equation 1 one arrives at Equation 4.

$$C=g-\frac{t}{K} \tag{4}$$

This equation can be written as follows:

$$t=K(g-C) \tag{5}$$

showing that the background t for the T counter is not equal to a multiple K of the background g of the Geiger-Mueller counter. One has to subtract the value C from g and then multiply with the efficiency K in order to get the background t.

The T counter had a volume which is 12% smaller than the Geiger-Mueller counter. This changes the constants of Equation 1 to those in Equation 6.

$$T=5.54(G-9.97) \tag{6}$$

or in other words the relative efficiency is approximately $K=5.5$ and the constant C is equal to 10 counts per second.

The background counts t and g each consist of two parts, which shall be indicated by an index o and an index c. t_o and g_o shall be that part of the respective backgrounds which is caused by gamma rays. These gamma rays are partly due to contamination of the metal parts of the counters. It is proper to assume that the number of contamination gamma rays is equal for the two counters. Because of the higher efficiency of the T counter in detecting gamma rays the count due to the gamma rays t_o will be K times g_o. The second part of the background t_c and g_c is due to directly ionizing particles such as penetrating particles of cosmic rays and of alpha rays which are emitted by the metal. Since the cosmic ray contamination for the T counter would be somewhat less than for the Geiger-Mueller counter due to the smaller cross-sectional area of the T counter, and since the alpha ray contamination for the T counter would be somewhat more than for the Geiger-Mueller counter due to the larger amount of metal in the cathode of the T counter, it can be assumed in good approximation that t_c is equal to g_c. These relationships are expressed in Equation 7 to 10.

$$t=t_o+t_c \tag{7}$$
$$g=g_o+g_c \tag{8}$$
$$t_o=K\times g_o \tag{9}$$
$$t_c=g_c \tag{10}$$

Combining Equation 5 with 7 and 8 one obtains Equation 11.

$$t_o+t_c=K(g_o+g_c-C) \tag{11}$$

By inserting values 9 and 10 into Equation 11 one obtains Equation 12.

$$K\times g_o+g_c=K(g_o+g_c-C) \tag{12}$$

and finally the relationship 13.

$$g_c=\frac{K\times C}{K-1} \tag{13}$$

By inserting the numerical values for K and C into 13 one obtains for g_c the value 12.2 counts per second.

$$g_c=12.2 \text{ cts./sec.} \tag{14}$$

This figure then represents that part of the background for the Geiger-Mueller counter which is due to directly ionizing rays.

From cosmic ray measurements it is known that the counting rate due to cosmic rays is approximately one counter per minute per square centimeter of counting area. The counter in question had a cross sectional area of 700 square centimeters. One may expect, therefore, a counting rate of approximately 700 counts per minute due to cosmic rays alone or a counting rate of 11.5 counts per second. This value agrees very well with the one which was calculated from the field observations and which is reported in Equa-

tion 14, and supports quite strongly the validity of the calculations made above.

The foregoing calculations show plainly that the background of the T counter (which is described more fully in U. S. Patent No. 2,397,071) does not increase proportionally to the increased efficiency for gamma rays. This is emphasized by the following tabulation of counting rates:

$T=$ 50	100	150	200	250
$G=$ 21	31	41	51	61
$5.5\times G=$115	170	225	280	335

The second line gives the observed counting rates with the Geiger-Mueller counters for the counting rate which is listed in the first line for the T counter. In the third line are the values which would be obtained if $K=5\frac{1}{2}$ Geiger-Mueller counters were used simultaneously. From the first and the last column it is apparent that the counting rate for the T counter increases by a factor 5, whereas the counting rate for $5\frac{1}{2}$ Geiger-Mueller counters increases only by a factor of 3. In other words, let us assume that there are two regions in the field, one of which shows a low counting rate and the other one a high counting rate. In the first region the T counter gives a rate of 50 and in the second region a rate of 250 counts per second. The T counter, therefore, shows a contrast by a factor of 5. If one now measures the same locations by using simultaneously $5\frac{1}{2}$ Geiger-Mueller counters each one of which has the same active value as the T counter one finds in the first place a counting rate of 115 and in the second location one of 335 counts per second. The aggregate of the $5\frac{1}{2}$ Geiger-Mueller counters, therefore, indicates a contrast which is slightly less than 3. This indicates clearly that the T counter has advantages which cannot be made up by using a large number of Geiger-Mueller counters.

In underground gamma ray surveys, the cosmic ray effect and hence the background, is diminished substantially by absorption in the overburden. However, in surface surveys (as shown by Fig. 1) the cosmic ray effect is high and in airborne surveys the background due to cosmic rays is even higher, and the tendency to obscure slight differences in gamma ray intensities from point to point is greater. This tendency may be overcome and satisfactory results obtained by employing a detector of the type just described, or any other type which has a substantially higher efficiency for gamma rays than the conventional Geiger-Mueller detector and in which this increased efficiency is obtained without increasing proportionately the counting rate for background. Hence anomalies in surface surveys that cannot be detected in reasonable time or reliably with Geiger-Mueller counters, even though a bundle of these are employed to increase cathode area and counting rate, may be detected with the multiple plate or crystal types of detectors.

From the foregoing, it is apparent that the multiple plate type of detector may be constructed with an efficiency for gamma rays of approximately 2.5% or say 5 times that of the conventional Geiger-Mueller counter.

If the relative accuracies of the T counter and the Geiger-Mueller counter are considered as they affect the useable portion of the total counting rate observed, it is readily apparent why the results obtained with the T counter are more accurate than those obtained with the Geiger-Mueller counter, even though a longer observation time is employed in using the Geiger-Mueller counter.

Assume the application of a T counter and a Geiger-Mueller counter of equal active volumes and a reading time for each which will result in the same number of total counts observed. This will give readings which are subject to the same probable statistical error as applied to the average counting rates observed. However, due to the lower efficiency for gamma rays of the Geiger-Mueller counter, this probable error is a much larger percentage of the useable counting rate (the observed counting rate with the background subtracted) than is the case with the higher efficiency T counter where the useable counting rate is a much larger portion of the total counting rate observed.

The invention, as applied to the location of buried mineral deposits through the discovery of radioactive anomalies associated with the country rock, contemplates underground, surface, and airborne operations employing any type of detector of requisite size and efficiency. Especially in underground operations, where the gamma ray intensities may be relatively high, Geiger-Mueller counters are sometimes useful. In surface and airborne surveys for the detection of faint anomalies characteristic of some mineralized zones as well as some faults, contacts, etc., i. e. when the invention is applied as an aid in geological mapping, the invention contemplates the use of the high efficiency counters already described.

Either positive or negative gamma ray anomalies may characterize a buried ore body. In some cases the country rock is more radioactive than the ore body and as the latter is approached the intensity of detected gamma radiation decreases. This is considered a negative anomaly, the reverse case in which gamma ray intensity increases as the ore body is approached being considered a positive anomaly.

A positive anomaly discovered in a survey of a deeply buried disseminated copper deposit in Arizona is illustrated in Fig. 2. In this survey a single multiple plate-multiple wire detector was employed. The envelope was a gastight brass cylinder 15" long and 3" in diameter. The cathode plates were silver and were grounded to the envelope. There were 65 such plates, each .010" thick and spaced on $\frac{3}{8}$" centers with their major surfaces perpendicular to the cylindrical axis. Seven tungsten anode wires (.005" dia.) were passed through $\frac{1}{2}$" holes in the plates. At each station the detector was laid approximately flat on the ground and 3000 counts were taken, the average probable statistical error for such a length of count being $\pm\frac{3}{4}\%$.

In all cases except stations 7 and 8 where the top of a hill had been flattened with a bulldozer, the stations were on substantially undisturbed ground, i. e. bed rock.

Consideration of the plot of gamma ray intensities, beginning at the right, shows substantially uniform and relatively low values over the schist. The contact of the schist with the granite porphyry is shown by an increase in intensity. Save for the readings at stations 7 and 8 (which may be less reliable than the others due to the disturbed surface), the intensities increase markedly as the depth to the ore body decreases with a strong increase in intensity at the left where the ore body is close to the surface. It will also be apparent that the detector distinguished between the granite and the granite porphyry of the overburden.

Fig. 3 is a vertical geological section through

a mineralized zone in Colorado with a graph of intensities observed at a series of stations on the surface above the section. In this work a single 3" diameter by 15" long multiple plate-multiple wire detector (similar to that used in the survey of Fig. 2) was employed. The ore bodies underlying the traverse are sulphide replacement deposits occurring along bedding planes in limestone. The limestones are interbedded with sandstones, grits and mudstones and there are several post-mineralization faults as shown. The rocks of the section are covered throughout by glaciofluvial gravels of varying depth and at no point is there a surface exposure of the ore.

The survey was begun on the uphill side of the section (the left side in Fig. 3). The first station was above unmineralized limestone overlain by gravel and a low intensity level of about 70 counts per second was registered. The second station is still to the left of the first ore body but the count at this point is substantially higher. The next four stations overlie the upper lead-zinc sulphide deposit, which is overlain at one point by a deposit of pyrite and pyrrohotite. All of them are points of high intensity, as is the next station (No. 6). Having in mind that the ore of this first body is nowhere closer to the surface than 10 feet and is over 100 feet below the surface at station 6, it is plain that the detector is beyond the range of detectable differences of gamma radiation originating in the ore body. This indicates the presence of a radioactive aura in the country rock overlying the body.

A second ore body of lead and zinc sulphide underlies the surface at the right of the section by depths in excess of 200 feet. Its presence is indicated by an increase in gamma ray intensity at stations 9, 10, 11, 12 and 13 which overlie it, the unmineralized zone between the two bodies being characterized by low intensities of stations 7 and 8.

Fig. 4 shows the results obtained in a horizontal underground gamma ray survey conducted along a crosscut in limestone in an Arizona mine. Three different limestones were crossed, as shown. A replacement deposit of zinc sulphide ore occurs in one of the lime formations and another one is cut by porphyry dikes. A marked aura occurs in Limestone A in the neighborhood of the dikes, i. e. there is a marked increase in gamma ray intensity from this lime at a substantial distance, i. e. in excess of 50 feet, from the dike.

An even stronger positive anomaly is associated with the zinc deposit which occurs close to a contact between the Limestone B and Limestone C. This anomaly is detectable at a distance of almost 200 feet to the left of the deposit in Limestone B in which it occurs but is less evident to the right, possibly because station No. 14, at which the intensity is relatively low, occurs almost on the contact between Limestone C and Limestone B. In other words, the contact or interface may have retarded the migration of gamma ray sources toward the right.

The survey illustrated in Fig. 4 was conducted with a 3" x 15" multiple plate multiple wire detector similar to that used in the survey of Fig. 2, the points of highest intensity being checked with a smaller multiple plate single wire detector 2" in diameter and 4" long. The detectors were stationary and substantially vertical in the center of the cross-cut at each station.

Fig. 5 illustrates an underground survey in a Utah mine in which lead-zinc sulphide deposits have replaced thin limestone beds in quartzite, with porphyry sills intruded along the bedding planes and generally parallel to the ore bodies. In this work a single small multiple plate detector was employed (2" diameter, 4" long) with 12 lead plate cathodes and a single coaxial tungsten anode wire. The porphyry sill, as might be expected of an acid intrusive, shows a marked positive anomaly, its aura in the quartzite being apparent at least 40 feet away. The vein on the left likewise is accompanied by a strong positive anomaly which is apparent in the quartzite at a substantial distance, indicating again the presence of an aura. Having in mind that in many cases exploration openings have missed valuable ore bodies by a matter of a few feet, the ability to locate an aura of a deposit, and thus in effect "see" through the intervening rock, is an extremely valuable aspect of the invention.

Figs. 6 and 7 illustrate actual underground gamma ray surveys made in accordance with the invention in a Montana mining district. In these surveys a single detector was employed with a metallic envelope 2" in diameter and 10½" long. It was provided with 51 silver cathode plates spaced as in the case of the apparatus employed in the survey of Fig. 2 and with a single coaxial anode wire of tungsten. The surveys were made along crosscuts about 2000 feet underground. In both cases the country rock was granite.

To consider Fig. 6, the gamma ray intensities beginning in the granite at the left are relatively high. In the neighborhood of the slight stringers of zinc ore a marked negative anomaly is encountered. Immediately thereafter however, the country rock to the left of the zinc-copper vein gives a high intensity which increases markedly as this vein is passed and then drops to the intensities observed in the unaltered granite. Continuing to the right, another sharp negative anomaly appears in the neighborhood of the zinc-lead vein.

The relationship of the stations at which the readings were taken to the position of the veins is shown at the bottom of Fig. 6. From this relationship it will be plain that the anomalies appear in the country rock well outside the veins.

Fig. 7 illustrates a traverse across a zinc vein which shows a marked positive anomaly. This anomaly is apparent in the country rock on both sides of the vein, as well as in the vein itself and illustrates clearly a situation in which the detector can apparently "see" the vein through several meters of granite, although what is actually being detected is the aura in the country rock, in this case granite, which lies adjacent to the vein.

One of the important fields of application of the invention is in surface reconnaissance, the detector being moved along the traverse continuously with continuous integrated observations. An efficient detector together with the associated power supply, preamplifier, amplifier, integrating circuit, registering meter, etc., with a total weight of less than 40 pounds has been constructed, and this unit may be carried by an observer walking along the traverse, a continuous indication of gamma ray intensities along the traverse thus being obtained. Larger detectors having a higher counting rate may be truck-mounted or airborne and anomalies have been detected while moving the detector along the traverse at speeds up to 200 miles per hour and at elevations up to more than one thousand feet.

All things being equal, greater contrast is obtained, i. e. the detection of significant anomalies

is more pronounced, if the detectors are carried along the traverse at a substantial distance above the ground, improvement in result being obtained as the distance is increased up to a height of about 150 feet, above which results become less satisfactory and more difficult to interpret.

A number of comparative surveys have been made in which the detectors were first mounted in a truck and run along the traverse and thereafter flown across the traverse in a helicopter at different elevations. In this work six large multiple plate-multiple wire detectors were employed. Each was 3 inches in diameter and 30 inches long and they were mounted side by side to form a bundle or panel. Each detector contained 136 silver cathode plates .010" thick mounted on 1/8" centers and 7 tungsten wire anodes (.005" dia.) passing perpendicularly through 1/2" diameter holes in the plates. Each detector was separately preamplified and quenched, the outputs of the several preamplifiers being sent to an electronic mixing circuit, which in turn fed a single amplifier. The output of this amplifier was integrated, and recorded by an electronic voltmeter. The integrator employed was so designed that its time constant, i. e. the time over which the input pulses were averaged, could be varied.

In the airborne surveys, as will presently appear from a discussion of Figs. 8 and 9, it was found that optimum results were obtained while flying at an elevation of 100 to 200 feet above ground, a height of about 150 feet being best. Extremely useful results, however, were obtained up to heights of 800 feet while flying over anomalies of relatively low gamma ray intensity. These effects of height upon result appear to be due to the interplay of a number of factors: viz.

1. At low altitudes above ground, i. e less than about 75 feet, slight differences in the altitude, encountered for example when the instrument is carried over a ditch, cause marked deviations in recording intensity. Since these deviations are not related to the geological features being investigated, they tend to obscure results. Above about 75 feet, these effects are less pronounced and hence there is less requirement for the pilot to attempt to fly at constant elevation above ground.

2. As height is increased, cosmic ray background increases and the intensities of gamma rays from the ground decrease, so that at above, say 800 feet, significant changes in gamma ray intensity due to geological differences to be discovered tend to be obscured unless they are very pronounced. As altitude increases, the path of the gamma rays through the air lengthens. This in turn reduces the intensity due to absorption by the air.

3. As height is increased, gamma ray intensity from any given point in the earth's crust decreases according to the inverse square law, but at the same time the area from which the detector receives gamma radiation increases. These factors oppose each other, so that the inverse square law is not the sole controlling factor.

4. At low elevations, radiation emanating from a buried source off to one side of the detector has to pass through a relatively long path in high density overburden with consequent high adsorption and marked decrease in intensity. As elevation above ground is increased the path through the overburden decreases, the net result being that this radiation may have a greater effect on the measurement, even though the total distance that the radiation travels through ground and air (which because of its low density has low absorptive power) is increased.

In the light of the foregoing, it would appear that even when the detector is carried along the surface at substantially constant distance above ground by animal or vehicle, and even when readings are made above the surface with the detector stationary, advantages accrue to increasing the elevation of the instrument above ground. Hence it is better to mount the detector above a truck rather than below and still better to mount the detector so that screening effect of the truck is minimized.

Several preferred mounting schemes for ground borne detectors are illustrated in Figs. 11 to 13.

Referring to Fig. 11 it will be seen that a panel of multiple plate-multiple anode detectors are mounted on a support above a vehicle, say an automobile, with their major axis (as defined by the anodes of the detectors) substantially parallel to the direction of travel of the vehicle. They are mounted sufficiently high above the vehicle, say 3 or 4 feet, that the absorption effect of the vehicle on gamma rays emanating from the surrounding terrain is reduced while the ground area from which the detectors receive gamma radiations is increased. The detectors are so disposed that their maximum cross sectional area is disposed approximately parallel to the path of travel and in a substantially vertical plane, so that they intercept gamma radiation from the sides of the traverse.

Fig. 12 illustrates a modification of the arrangement of Fig. 11, in which the detectors are broken into two separate panels of three each disposed respectively on the two sides of the vehicle but electrically connected as already described with separate preamplifiers feeding a common mixer.

Fig. 13 illustrates another modification of the arrangement of Fig. 12 in which the axes of the detectors are vertical, the arrangement being otherwise the same.

All three of the foregoing arrangements are advantageous in surveys conducted over undisturbed surfaces and also along established roads, where fills, pavement, etc., may tend to obscure results. They permit increased reception from undisturbed terrain along the side of the road and thus tend to improve reliability of result.

A comparison of results obtained with automobile mounted and airborne detectors employed to traverse a granite plug occurring in sandstone in Texas is given in Fig. 9. The lowest trace on this figure was obtained with the panel of six detectors mounted horizontally on the roof of an automobile driven along the traverse at a speed of about 35 miles per hour. The other traces were obtained with the same panel of detectors mounted in a helicopter and flown along the traverse at the elevations and speeds indicated for each trace. In all cases the "time delay" i. e. the integration constant of the integrating circuit interposed between the amplifier and the recorder was the same, so that the results are directly comparable.

To consider the lowest trace, obtained with the detectors mounted on the automobile, and beginning on the right, it will be seen that the contact between the sandstone and the granite and schist occurring on the right of the plug is marked by a substantial increase in intensity of gamma rays. The contact between the granite-schist and the fresh granite is less marked but is distinguishable as a small negative anomaly, where-

as the contact between the fresh granite and the sandstone at the left of the figure is marked by a sharp decrease in intensity as the detector passes toward the sandstone. This trace shows clearly the pronounced effect of surface features on the detector at low elevations. Thus when the detectors were carried across a bridge over a dry creek bed, so that their distance above ground increased a few feet, there was a sharp drop in intensity. The survey which the lowest trace represents was made along a paved highway, and it is to be expected that better results might be obtained over undisturbed ground, although not as good as those obtained with the airborne instruments.

The trace obtained when the detectors were flown across the traverse at an elevation of about 100 feet has the same general shape as that of the trace taken immediately above ground level. In general, however, the trace at 100 feet is smoother and non-significant variations in intensity (such as that due to the dry creek) are less pronounced, so that the significant deviations representative of geological features are easier to detect. For example, at 100 feet the contrast between granite and sandstone and that between granite and granite-schist are substantially greater.

The trace obtained at 150 feet above ground is still better than that obtained at 100 feet, despite the fact that the speed of travel was considerably greater (i. e. 60 M. P. H.). Thus the trace is in general smoother, insignificant variations being minimized while the indices of the contacts between rocks are more easily recognized. So, although the trace has the same general shape as those taken at the lower elevations, the several formations are more sharply defined and there is less "hash" on the trace.

At an elevation of 200 feet, as shown by the upper trace, the several formations are still sufficiently defined to be identified. However, contrast between formations has in part been lost, and the trace is not so easy to interpret as that made at 150 feet above ground.

Fig. 8 continues the comparison of traces made with airborne detectors at different elevations across the same granite plug surveyed in Fig. 9. The detection equipment and the aircraft were the same as in the operations illustrated by Fig. 9, but a different time delay, i. e. integration constant was employed in recording the traces. Surveys were run at elevations of approximately 100, 200, 400, and 800 feet above ground at approximately the same air speed (35 M. P. H.). The four traces thus obtained are shown. All of the traces follow the same general pattern, but as elevation is increased minor and insignificant variations tend to be removed. The traces at 100 and 200 feet show the greatest contrasts for the several geological formations and features to be identified, but differences between the sandstone and the fresh granite, between the granite and the granite-schist and between the granite-schist and the sandstone are still apparent at 400 and 800 feet. In short, Fig. 8 shows that the optimum altitude for airborne gamma ray surveys in accordance with the invention is between about 100 and 200 feet, but that useful results, even with relatively low intensity anomalies, can be obtained up to 800 feet. In still other tests, flown in an airplane, as distinguished from a helicopter, and at much higher speeds and elevations, high intensity anomalies (such as inshore line where there is a strong contrast between gamma ray intensities emitted by land and water) were detected clearly. Eight hundred feet, therefore, is not necessarily an upper limit of usefulness of the invention, although it is well above the optimum elevation of about 150 feet, at which height the effects of deviations in elevation above ground are less pronounced, and less care need be taken in maintaining constant this elevation.

From the foregoing discussion of Figs. 8 and 9, it will be plain that by continuously integrating the pulses as a function of time and adjusting the integration time constant in relation to the speed of movement of the detector over the surface being investigated it is possible to emphasize contrasts in gamma ray intensities due to geological changes (say at a contact between different rocks) or geological differences in the earth underlying the line of movement of the detector while suppressing contrasts in gamma ray intensities due to surface features (say the presence of a ditch). For any given speed of movement of a detector at a given elevation, there is an optimum integration time constant, and the invention contemplates the adjustment of time constant in relation to speed of detector movement or height above ground or both, in order to secure maximum contrast between significant gamma radiation along the line of detector movement, either at substantial elevations or at the surface.

It will also be plain that for a given integration time constant, the speed of movement of the detector over the terrain should be kept sufficiently low that differences in gamma ray intensities due to geological changes in the earth underlying the line of movement of the detector are not obscured by the integration.

In airborne surveys conducted in accordance with the invention it is essential that the traces obtained, say those of Figs. 8 and 9, be correlated with the terrain over which the survey is made. This may be done in several ways.

One simple way is to provide an automatic time marker in the recorder, so that the time each portion of the trace is recorded is known. The operator of the detector notes the exact time that the aircraft is directly above prominent landmarks along the traverse, or above monuments or markers disposed on the ground along the traverse, and thus is able to correlate surface with trace by means of time.

Another but more complicated method is to employ a camera which is geared to the recorder of the detector. In this way a series of pictures of the underlying terrain is taken as the traverse is flown simultaneously with the recording of the trace of radiation intensity and correlated therewith.

A third method involves the use of radioactive markers which are disposed at selected points along the traverse and are registered on the trace itself. It has been established, as shown in Fig. 10, that a 5 mg. source of radium gives a sharp "pip" on the trace at elevations up to at least 160 feet. These "pips," should they happen to coincide with a gamma ray anomaly in the ground, may be confusing. In order to avoid possibility of such confusion it is desirable to repeat the survey without employing the radioactive markers and comparing the two traces thus obtained. Another way to avoid confusion is to employ two radioactive markers spaced from each other far enough to produce two pips on the

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trace and thus produce a characteristic and easily recognizable pattern.

Referring to Fig. 10, the trace "A" was obtained while flying at an elevation of 20 feet at a speed of about 30 miles per hour over a point at which a 5 mg. source of radium was subsequently placed, the detectors employed being the panel of 6 previously described. The flight was repeated at an elevation of 20 feet (trace "B") with the radium source in place and a pronounced "pip" was obtained, so pronounced in fact that it ran off the scale. Additional repeat runs were made at elevations respectively of 40, 80, 160, 300, and 400 feet (traces C, D, E, F and G). The pip is pronounced up to 160 feet, and recognizable even at 400 feet.

A 5 mg. source of radium is extremely small, again indicating the surprising nature of the results obtained and the high efficiency of the multiple-plate type of detector for gamma rays. This efficiency is further illustrated by the fact that a 100 mg. source of radium buried in the ground to a depth of 6 feet is undetected by a modern ionization chamber, but may be found easily with a multiple plate-single wire counter of the type described in connection with Fig. 5.

The aspect of the invention illustrated in Fig. 10 (which involves determining the location of an aircraft with respect to terrain over which it is flying by detecting from the aircraft the increase in gamma radiation from a source, such as a small quantity of radium, located at a known point on the terr [illegible]) is useful outside of the prospecting field and is in fact of general utility in blind flying. Thus the position of an airfield or any other ground installation may be marked by placing radioactive markers at known locations, say at the four corners of a field. A gamma ray detector of relatively high efficiency is mounted in an aircraft, and a strong "pip" will be indicated by the recorder or indicator of the detector when the aircraft is over the source. In order to distinguish one monument or marker from another, the size of the radioactive sources employed may be different, or a monument may consist of a plurality of separate sources spaced far enough apart in a horizontal direction that each produces a substantially separate pip, thus producing at the recorder a distinctive pattern. For example, one corner of a field may be marked with one source, a second with two, etc., or a distinctive pattern may be produced by employing as a monument a plurality of spaced sources of different sizes.

The height at which the gamma ray point source is detectable is a function of the size. As shown in Fig. 10, a very small source is easily detected at heights in excess of two hundred feet, and by increasing the size of the source the height may be increased to several thousand feet.

Air navigation through the application of a system of radioactive markers (say point sources of radium) at known ground locations offers outstanding advantages, first because the emission of gamma rays by the marker is assured, whereas lights, radio beacons, etc., may fail through failure of current. The radioactive marker is, therefore, more reliable and may be detected with simple reliable equipment irrespective of weather conditions, etc. Secondly, the intensity of the received radiation, as indicated by the height of the pip, is an index of the height of the aircraft above the marker.

Although 150 feet, or at least some distance between 100 and 200 feet now appears to be the optimum height for observation of gamma ray intensities in airborne surveys conducted in accordance with my invention, local conditions may require a different height for maximum contrast, and the invention contemplates broadly the practice of flying a detector across terrain at an elevation above ground such that maximum contrast is obtained between gamma radiation from the earth and other detected radiation. Preferably this detection is made continuously and the course flown is at least approximately a constant distance above ground.

Surveys made in accordance with my invention have shown that a given type of occurrence in a given locality (say a copper vein in granite in one mining district where the copper veins have been formed under similar conditions and sometimes at about the same time) will manifest a typical anomaly. In such case, it is advantageous to survey one or more known deposits to determine the typical anomaly and to look for similar anomalies in the neighborhood which are not associated with known deposits, but which may reveal one hitherto undisclosed. This is an important feature of the invention and one which tends to reduce the prospecting risk substantially. It is not necessary that the known deposit which is surveyed be intact at the time it is surveyed, for it has been demonstrated that the anomaly remains after the deposit has been mined out, in whole or in part. Consequently a survey in the neighborhood of a deposit which has been removed may establish the type of anomaly to be sought in surveys conducted in the neighborhood to locate extensions of the deposit or similar new occurrences.

As applied to the discovery of anomalies indicated by differences in the intensity of gamma rays emitted from different points in the overburden of a mineral deposit, the invention contemplates surface and underground operations, the term surface being employed to include those conducted on the surface as well as above the surface, i. e. with airborne instruments. The discovery of the anomalies in undeground operations may be made by surveys conducted along bore holes or development openings such as raises and crosscuts.

When employing counters having a substantially higher efficiency than conventional Geiger-Mueller counters but in which the counting efficiency for background does not increase proportionately to the increase in gamma ray counting efficiency, the invention has more general application in surface operations and may be used not only to discover such anomalies but also as an aid in geological mapping, i. e. in the discovery of contacts, etc. The method may thus be used to cover a large area rapidly and cheaply with airborne instruments. The results obtained will permit accurate geological mapping of the terrain, but in the normal case most of the area will yield only negative results from the standpoint of locating mineral deposits, i. e. no substantial anomalies will be observed. In those portions of the area in which anomalies are observed in this large scale reconnaissance, detailed investigations should follow, either with airborne equipment or on the ground using a detector which is carried by man, animal or vehicle.

I claim:

1. In geophysical examinations involving detection and measurement of the intensity of gamma rays emitted from the earth at different locations along a traverse of an earth surface,

the improvement which comprises detecting the gamma radiation with a bundle of pulse-type detectors and integrating the combined output of the detectors as a function of time.

2. In geophysical examinations involving detection and measurement of the intensity of gamma rays emitted from the earth at different locations along a traverse of an earth surface, the improvement which comprises detecting the gamma radiation with a bundle of pulse-type detectors and integrating the combined output of the detectors as a function of time while moving the detectors along the traverse as the integration occurs.

3. In geophysical examinations involving detection and measurement of the intensity of gamma rays emitted from the earth at different locations along a traverse of an earth surface, the improvement which comprises detecting the gamma radiation with a bundle of pulse-type detectors, the aggregate active volume of which is relatively long in the direction of the traverse and relatively short in a direction transverse to the traverse and integrating the combined output of the detectors as a function of time.

4. In geophysical examinations involving detection and measurement of the intensity of gamma rays emitted from the earth at different locations along a traverse of an earth surface, the improvement which comprises detecting the gamma radiation with a bundle of pulse-type detectors, the aggregate active volume of which is relatively long in the direction of the traverse, relatively long in a direction perpendicular to the earth surface and relatively short in a direction transverse to the traverse and parallel to the earth surface and integrating the combined output of the detectors as a function of time.

5. In geophysical examinations involving detection and measurement of the intensity of gamma rays emitted from the earth at different locations along a traverse of an earth surface, the improvement which comprises detecting the gamma radiation with a bundle of pulse-type scintillation detectors and integrating the combined output of the detectors as a function of time.

6. In geophysical examination involving measuring the intensity of gamma rays emitted from the earth, the improvement which comprises moving a bundle of pulse-type detectors for gamma radiation along a traverse of an earth surface but at a substantial distance from that surface, integrating the combined output of the detectors as a function of time employing an integration time constant, and adjusting the integration time constant to the speed of movement of the detectors over the earth surface so as to emphasize contrasts in gamma ray intensities as indicated by the integrated output and due to geological differences in the earth along the traverse.

7. In geophysical examination involving measuring the intensity of gamma rays emitted from the earth, the improvement which comprises moving a bundle of pulse-type detectors for gamma radiation along a traverse of an earth surface but at a substantial distance from that surface, integrating the combined output of the detectors as a function of time employing an integration time constant, and adjusting the integration time constant to the distance of the detectors from the earth surface so as to emphasize contrasts in gamma ray intensities as indicated by the integrated output and due to geological differences in the earth along the course of the traverse.

GERHARD HERZOG.

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Aug. 31, 1954 J. H. ANDREWS 2,688,095

X-RAY CAMERA FOR UNDERGROUND GEOLOGICAL EXPLORATION

Filed June 3, 1953 2 Sheets-Sheet 1

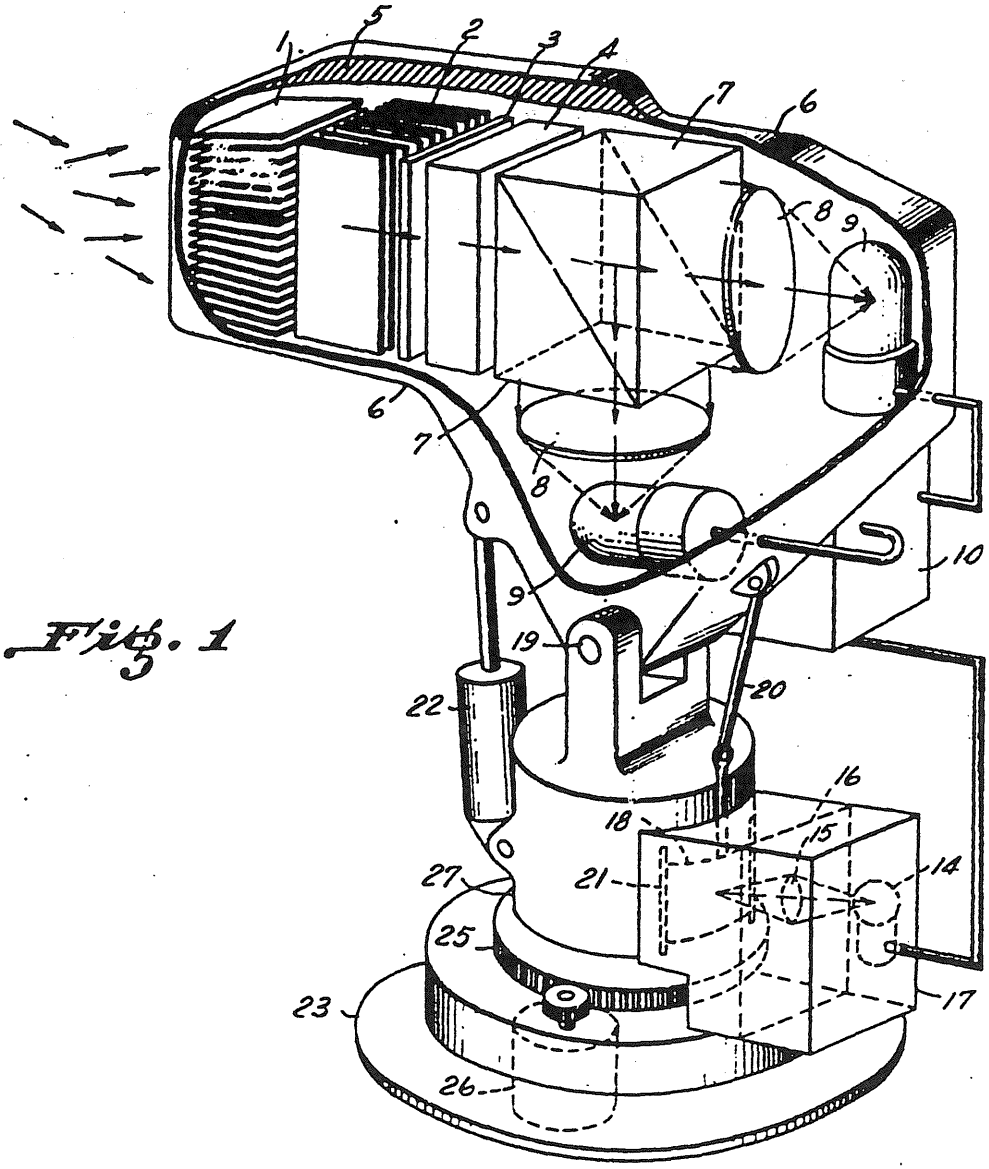

Fig. 1

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X-RAY CAMERA FOR UNDERGROUND GEOLOGICAL EXPLORATION

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Fig. 2

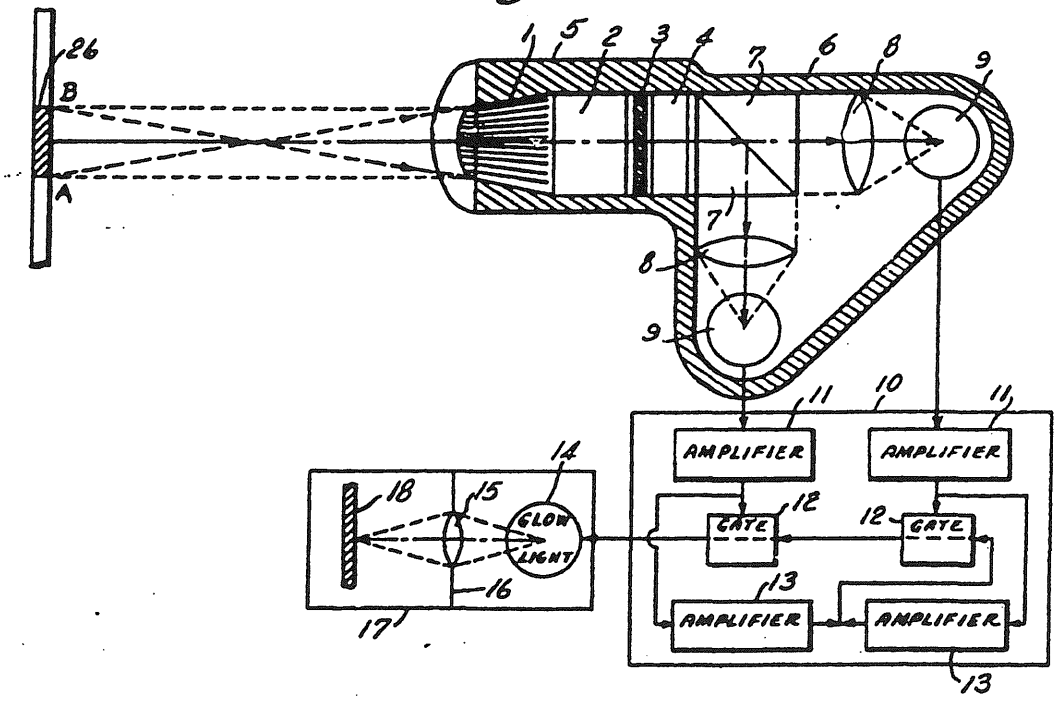
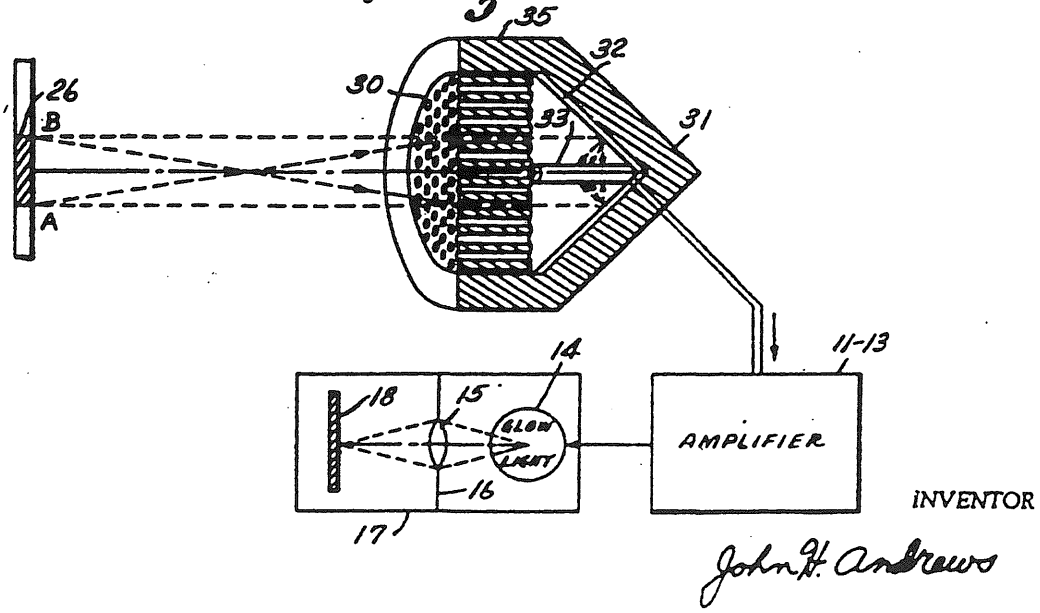


Fig. 3



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Patented Aug. 31, 1954

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UNITED STATES PATENT OFFICE

2,688,095

X-RAY CAMERA FOR UNDERGROUND GEOLOGICAL EXPLORATION

John H. Andrews, La Mesa, Calif.

Application June 3, 1953, Serial No. 359,385

2 Claims. (Cl. 250—65)

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This invention concerns an apparatus for detecting and recording in photographic picture form images of X-rays, gamma rays, and other radiations having short wave lengths emitted from the earth and other bodies.

Previous X-ray cameras for photographing natural radiations have been of the pin-hole type and because of the small hole diameter necessary to produce an understandable picture, only a very small portion of the natural radiations were allowed to expose the film. This restriction on the amount of the radiations entering the camera has previously prevented the making of photographs of anything other than highly radioactive bodies using their own natural radiations to expose the film.

Unlike light rays or cathode rays, short wave length radiations such as X-rays, gamma rays, etc. are not reflected, refracted, or deflected appreciably by ordinary methods. It is therefore an object of this invention to provide an apparatus which will give the effect of an optical camera wherein natural radiations of low intensity and of short wave length cause a light to expose a photographic film yielding a picture of the relative strengths and directions of these radiations as they exist in nature.

It is a further object of this invention to provide a camera that will take in more of the emitted radiations from a body or bodies than previous cameras.

A still further object is to provide a camera type apparatus that is sensitive to emitted radiations and has the ability to amplify such radiations for recording thereof.

Another object is to provide an apparatus which is capable of investigating radioactive static at the earth's surface.

A still further object is to provide an apparatus which is capable under certain circumstances of making a type of photographic recording of subterranean formations, buried objects, etc.

Still other objects and attendant advantages of the invention will become apparent from a reading of the detailed description in conjunction with the drawings therein:

Figure 1 shows a broken-away perspective view of one embodiment of my invention.

Figure 2 shows schematically the general arrangement of the filters, optical components, and the electrical circuit for the apparatus shown in Figure 1.

Figure 3 shows schematically another embodiment of my invention wherein another type of filter has been shown together with another type

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of detector arrangement utilizing a reflector shaped diffraction means.

The method of accomplishing the desired result of this invention is by directional filtering, scanning, conversion of radiations to electrical signals, amplification of these electrical signals, conversion of these electrical signals to light signals, and photographing these light signals on to a film whose scanning movements are synchronized with those of the filter and detector.

X-rays, gamma rays and other short wave length radiations with ionizing properties emitted by the earth and other bodies arrive from random directions at the entrance to the camera in front of filter 1 (Figure 1). Filter 1 and filter 2 are both composed of a series of nearly parallel plates with small spaces between each plate. The plates may be made from metal or other dense material. The spaces between each filter plate and its neighbor in a series may be closer at the front than at the back or each plate may be tapered in thickness with the thick part forward. These two mediums when used separately or in combination will facilitate the directional control of the radiations by the filters. The direction of the plates composing filter 1 and filter 2 are at 90° to one another and the resultant effect of the two sets of filters in combination is to absorb all radiations except those having their direction substantially parallel to the axis of the camera. The dimensions of the filter plates and the spaces in between plates are such that they cause the camera to be "focused" upon a small distant area "A—B" of the emitting body as is shown in Figure 2. In place of using two sets of parallel plates for the directional filters as is described above, a single thick plate 30 of dense material may be substituted if it is honeycombed with a multitude of parallel or slightly converging holes through it as is shown in Figure 3.

After having been filtered, the radiations pass through window 3 which is opaque to light but transparent to X-rays, gamma rays, etc. Window 3 is the front of a light tight compartment 6 which houses the detection apparatus. Light tight compartment 6 also forms part of the housing which supports the filters, detection apparatus, and optical system and also protects the detector head from stray radiations including cosmic rays which would cause this instrument to yield false information. Those parts of the detector head which are particularly vulnerable to cosmic ray bombardment are protected with extra thick shielding 5 which may also form part of the housing 6, as shown.

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Directly behind window 3 is a plate 4 of polystyrene, potassium iodide, naphthalene crystals, or other substance which will generate light when exposed to ionizing radiations. Behind plate 4 is a combination optical prism 7 which divides the light generated by the plate 4 and transmits it to lenses 8 where the light is condensed and forwarded on to two or more multiplier phototubes 9. Upon striking each multiplier phototube, the light causes each tube to generate an electrical signal which is fed into the input of amplifier 11.

Since present day multiplier phototubes have an inherent high noise level generated within the tube itself, it is desirable to use two or more multiplier phototubes connected to a gating circuit which passes a signal only when the signal is detected and reported by all multiplier phototubes instantaneously. This gating may be accomplished by a circuit of the type shown in Figure 2 having an input amplifier 11, an output amplifier 13, and a relay or gate 12 for each multiplier phototube used. The output of each multiplier phototube controls the output signal intensity of its output amplifier 13 and also controls its gate or relay 12 through its input amplifier 11. Each gate is in series with the gates of all other phototubes. The output currents from all output amplifiers are connected in parallel and the combined current must pass through all of the gates 12 in order to operate the glow light 14. The gates 12 may be either electromagnetic relays or grid controlled gas tubes of the Thyratron type.

If the high noise level of the multiplier phototube is not objectional for certain applications, a single multiplier phototube may be used and prism 7 and the gating mechanism 12 may be eliminated from the above.

The intensity of the light given off by the glow light 14 varies directly with the signal strength of the signal from output amplifiers 13. The glow light may be either a filament type or a gas filled tube. The light from this light 14 is condensed by means of lens 15 and focused upon a photographic film 18 both of which are inside of a light compartment 17.

In order for the radiation intensity from distant area "A—B" (Figure 2) to have meaning, it must be combined in photographic form with all of its neighbor elements of area. This is accomplished by means of a two directional scanning motion of the entire detector head and a duplication of these motions between the image of the glow light 14 on the film and the film 18. To permit scanning, the camera base 23 is equipped with a means for rotation around or back and forth about a vertical axis. The rotating portion of the base 27 has means mounted thereon for progressively tilting the detector head in elevation about a pivoted mounting 19. The driving mechanism as shown in Figure 1 is a motor driven 26 gear drive 25 for rotation of the base 27 about its vertical axis and a hydraulic cylinder 22 for tilting the detector head. Any other mechanism for tilting and rotation such as racks and gears, ratchets, lead screws, linkages, hydraulic cylinders, etc. could be used to produce these motions, if desired.

To simplify the illustration (Figure 1), the film support rack 21 is shown attached to the rotating portion 27 of the support base while the light source 14 and its optical lens 15 and light tight case 17 are shown as part of the fixed or nonrotating part of the base 23. Any suitable light tight seal such as felt could be secured to the contact surfaces of case 17 which are in adjacency to the outer surface of the rotatable base 27. This arrangement permits exact duplication of rotational motion by the photographic reproduction unit in case 17 of the motion of the detector head. The vertical movements of the detector head are transferred from the head 6 to the film 18 through linkage 20. Alternatively, both of the above described motions could be transferred from the head to a remotely located reproduction unit by means of selsyn motors or other remote control devices.

Another embodiment of my invention is shown in Figure 3 as a schematic section of the reflector type detector head and associated electrical equipment. Those unidirectional radiations passing through the filter 30 strike a reflector 31 whose inside surface is coated with crystals 32 or is covered with a ruled diffraction grating. Part of the energy from the filtered radiations passes through the crystals 32 or grating and is absorbed within the shielding composing reflector 31. Much of the remaining energy striking the crystals or grating is diffracted or dispersed in all directions. A portion of this dispersed energy arrives at the collector device 33 which may be an ionization chamber, a Geiger Muller type tube, or other radiation sensitive device. The generated signal from this radiation sensitive device 33 controls the output of amplifier 34 which in turn operates the glow light 14 described above. The shape of reflector 31 is optional depending upon the length of the collector tube but a conical reflector is satisfactory for most units. The entire detector head is surrounded with a heavy shielding 35 which blends into and forms the reflector at the rear of the head. This shielding is necessary to protect the collector tube 33 from unwanted radiations.

It is obvious that various changes and modifications may be made in the details of construction and design of the above specifically described embodiment of this invention without departing from the spirit thereof, such changes and modifications being restricted only by the scope of the following claims.

I claim as my invention:

1. A camera for recording indications of radiations of short wave lengths, said camera comprising means for directionally filtering short wave length radiations, means for detecting radiations passing through said filter means and being operative to generate a signal in response and proportional to said detected radiations, means for supporting and moving said filtering and detecting means for movement in a scanning pattern, a light source being energized in response to and proportional in intensity to said signal, and means for imparting relative movement between said light source and a photosensitive recording medium in synchronism with the scanning movements of said filter and detector means, said detector means having a plate composed of an ionizing radiation sensitive substance behind said radiation filter, said plate being operative to generate a signal of light varying in intensity proportional to the intensity of the impinging ionization radiations, said signal light being able to pass through an optical light refractive means operable to separate said signal and to pass the same in at least two directions, a pair of light sensitive signal generative means spaced from said light refractive means and in the path of said refracted signals, and means operably con-

nected to the output of said light sensitive means operable to compare the signals received therefrom and to pass said signals only when said signals are substantially equal, the output of the last said means being operably connected to said light source to operate said light source, said light source being operable in response to said last named output.

2. A camera for recording indications of radiations of short wave lengths, said camera comprising means for directionally filtering short wave length radiations, means for detecting radiations passing through said filter means and being operative to generate a signal in response and proportional to said detected radiations, means for supporting and moving said filtering and detecting means for movement in a scanning pattern, a light source being energized in response to and proportional in intensity to said signal, and means for imparting relative movement between said light source and a photosensitive recording medium in synchronism with the scanning movements of said filter and detector means,

said detector means having a reflector shaped means behind and in the path of said radiation filter, the surface of said last named means being diffractive in character, said last named means being operable to transmit a portion of the energy of the filtered ionizing radiations to said detecting means, said detecting means being disposed within the focal region of said reflector shaped means, and the volume enclosed by said reflector shaped means being shielded from unfiltered radiations.

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SULFUR CRYSTAL COUNTER

Filed Feb. 26, 1952

FIG. 1.

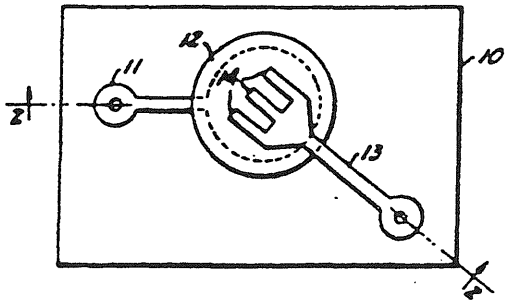


FIG. 2.

FIG. 3.

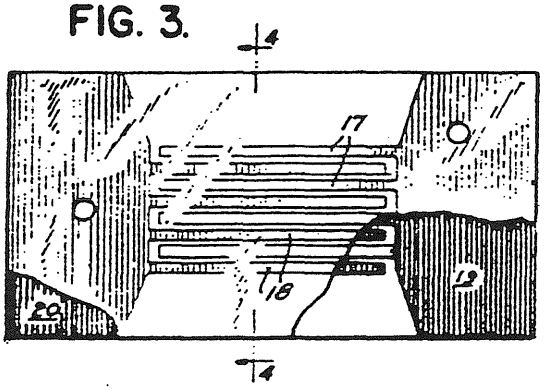


FIG. 4.

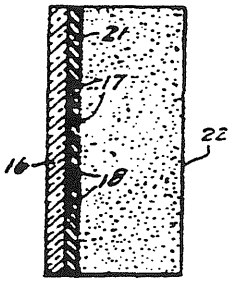
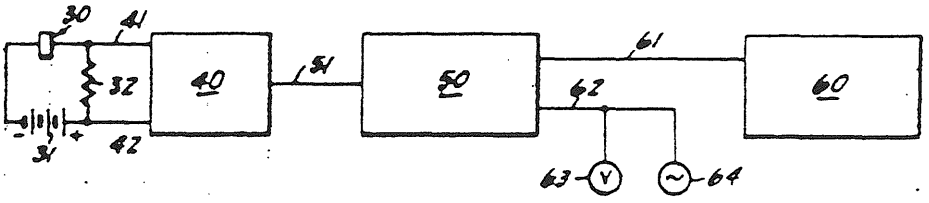


FIG. 5.



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United States Patent Office 2,717,964 Patented Sept. 13, 1955

2,717,964

SULFUR CRYSTAL COUNTER

Vescan Lawrence Parsegian, Brooklyn, N. Y., and Ralph Carrol Maninger, Montvale, N. J., assignors to the United States of America as represented by the United States Atomic Energy Commission

Application February 26, 1952, Serial No. 273,488

5 Claims. (Cl. 250—83.3)

This invention relates to a new and improved apparatus for the detection of radioactive particles. With the increasing use of radioactive substances, new types of radiation detectors have to be developed to provide better accuracy and sensitivity than is presently available in conventional instruments. Crystal counters have been investigated because they offer several advantages. They are small in size and, therefore, permit good counting geometry in experiments. Their low resolving time allows both high-speed counting and fast coincidence counting. However, crystal counters now being used are no more sensitive than the more conventional ionization chambers. That is, the conversion of energy from radioactive particles into ion pairs takes place at the same rate for the ionization chamber as for the usual crystal counter. On the other hand, an apparatus embodying the present invention has a much higher rate of energy conversion in addition to the other advantages attributable to crystal counters. This higher energy conversion results in a more efficient counter and a higher signal-to-noise ratio.

An apparatus can also be fabricated, using the method of the present invention, which will be capable of detecting and measuring alpha particles in the presence of high level beta and gamma radiation.

It is accordingly an object of the present invention to provide a new and improved crystal counter for radioactive particles.

A second object is to provide a new and improved sulfur crystal counter.

Another object of the invention is to provide a polycrystalline sulfur counter which will detect and measure alpha particles in the presence of intense fields of beta and gamma radiation.

More particularly the present invention relates to an apparatus for the detection of radioactive particles which includes a polycrystalline sulfur film, two electrically conductive electrodes contiguous with the sulfur film, means for establishing a potential difference between the electrodes and means for measuring current flow between the electrodes.

The many objects and advantages of the present invention may best be appreciated by reference to the accompanying drawings, the figures of which illustrate apparatus incorporating preferred embodiments of the present invention and capable of carrying out the method of the invention. In the drawings:

Figure 1 is a plan view of a preferred embodiment of the apparatus.

Figure 2 is a sectional view taken along the line 2—2 of Figure 1.

Figure 3 is a plan view of a second embodiment of the apparatus.

Figure 4 is a sectional view taken along the line 4—4 of Figure 3.

Figure 5 is a schematic diagram showing the relationship between the crystal counter of the present invention and conventional electronic apparatus for measuring the response of the counter.

Referring to Figures 1 and 2, the counter is fabricated on a glass slide 10. On the upper surface of slide 10 is evaporated an electrically conductive coating to form electrode 11. Electrode 11 is contiguous with the underside of a polycrystalline film of sulfur 12 deposited thereon. Evaporated on to the other side of sulfur film 12 is a fork-shaped electrode 13 containing finger-like extensions 14. For the purposes of clarity, the thickness of the component parts of the counter shown in Figure 2 has been greatly enlarged. It is also apparent that electrodes of any shape may be formed by properly masking the other parts of the counter while the electrode evaporation and deposition is taking place. It should be noted that the finger-like extensions 14 on electrode 13, while providing good electrical contact with the sulfur film 12, also provide a small area with respect to electrode 11. Therefore, a minimum of electrical capacity is achieved while still maintaining good electrical conduction characteristics.

In operation, a difference of potential is applied between electrodes 11 and 13 by any suitable leads, not shown. Under normal conditions sulfur acts as an electrical insulator so that no conduction of current between electrodes 11 and 13 will occur. However, we have found that when the sulfur is placed in a radioactive field, radioactive particles impinging on the sulfur will form ion pairs therein and provide a current conduction path between electrodes 11 and 13. Therefore, by measuring the amplitude and the rate of occurrence of the resulting current pulses between electrodes 11 and 13, an indication of the intensity level of the radiation field is obtained.

Referring to Figure 5, a block diagram of an apparatus for measuring the response of the counter is shown. The counter, indicated generally by the arrow 30, has one side connected to the negative side of a direct current power supply 31. The other side of the counter is connected to the positive side of supply 31 through a resistor 32. Across resistor 32 is connected the input of a conventional low noise preamplifier 40 by means of conductors 41 and 42. The output of preamplifier 40 is connected to the input of a conventional linear amplifier 50 through conductor 51. The amplifier 50 output is applied to a scaler 60 by means of conductor 61 and is also applied on conductor 62 to a voltmeter 63 and an oscilloscope 64.

When the crystal counter is placed in a radioactive field, the radioactive particles impinging on counter 30, form a conductance path, as described herein above, with a resulting current flow between the electrodes. The current passing through resistor 32 gives rise to a voltage pulse applied to the input of preamplifier 40 by means of conductors 41 and 42. The amplified pulse is applied on conductor 51 to amplifier 50 where further amplification takes place. The output of amplifier 50 is applied through conductor 61 to scaler 60 where it is counted and recorded. By recording the number of current pulses occurring in a measured time interval, it is possible to determine the number of particles per second arriving at the counter 30. The amplitude of the output pulse of amplifier 50 can be measured by either voltmeter 63 or oscilloscope 64.

Electronic instruments which have been found satisfactory for measuring the output pulses of the sulfur counter are a Model 204–B linear amplifier manufactured by the Atomic Instrument Company of Boston, Massachusetts, and a Model GS–6 scaler manufactured by the Technical Associates Company of Glendale, California. Measuring instruments such as the Hewlett Packard Type 400A Vacuum Tube Voltmeter and the Dumont Type 208 oscilloscope can also be used.

Another form of sulfur counter embodying the pres-

ent invention is shown in Figures 3 and 4. In this embodiment the crystal counter is mounted on a glass plate 16 and is fabricated in the following manner: The plate glass 16 is coated completely with an electrically conductive plating such as aluminum. An interlacing finger-like electrode structure is scribed in the aluminum to form a plurality of lateral extensions or "fingers" 17 and 18 spaced from each other. All of the "fingers" 17 are connected to a section 19 of the solid coating and the "fingers" 18 are connected to a section 20. A polycrystalline sulfur film 21 is then deposited over the entire electrode structure and between the "fingers" 17 and 18. In this embodiment, therefore, both electrodes are on the same side of the sulfur film but are electrically insulated from one another. This electrode structure again has the advantage that adjacent electrode areas are very small, thereby providing minimum electrical capacitance therebetween but still permitting a good electrical conductance path. This embodiment operates in the same manner as the counter described with respect to Figures 1 and 2. The impinging radioactive particles release ions in the sulfur film and provide conductance paths between adjacent electrodes. The resulting current flow may be measured with the circuit of Figure 5 or any similar conventional current measuring circuit.

If the polycrystalline sulfur film is deposited in a very thin layer, for example, in the order of 20 to 40 microns thick, excellent discrimination between alpha particles and beta and gamma radiation results. The beta and gamma particles pass through the thin sulfur film without any effect but the less penetrating alpha particle will be absorbed in the sulfur film. The resulting conduction current between the electrodes is due solely to the ion pairs formed by the alpha particles.

In the usual crystal counter or air ionization chamber, an alpha particle with an energy of two million electron volts will form approximately fifty-seven thousand ion pairs or one ion pair for approximately every thirty-five electron volts. On the other hand, a polycrystalline sulfur counter fabricated in the manner described herein can form approximately three hundred thousand ion pairs in response to an alpha particle of one million electron volts or one ion pair for approximately every six electron volts. The sulfur crystal counter is, therefore, approximately six times as sensitive as the usual crystal counter.

Typical dimensions of a counter that has operated satisfactorily is a sulfur film thickness of thirty-five microns with spacing between electrode "fingers" of ten to one hundred microns. The difference of potential applied between electrodes was four hundred and seventy volts.

The sulfur crystal counter can also be used as part of an improved scintillation counter by depositing a luminescent material 22 such as anthracene on the sulfur film 21 of Figure 4. It is known that radioactive particles impinging upon such a luminescent material will cause it to emit photons. It has been found that the response of thin polycrystalline films of sulfur to photons is similar to that above-described for radioactive particles. Therefore, the sulfur crystal will release an amount of ions proportional to the number of impinging photons. The ions can be detected by a circuit such as the one shown in Figure 5. The subject counter can, therefore, be used in a manner similar to more expensive photomultiplier tubes but occupying a much smaller space than presently available tubes.

While the salient features of this invention have been described in detail with respect to a few embodiments, it will, of course, be apparent that numerous modifications may be made within the spirit and scope of this invention and it is, therefore, not desired to limit the invention to the exact details shown except in so far as they may be defined in the following claims.

We claim:

1. Apparatus for the detection of radioactive particles which comprises, in combination, a polycrystalline sulfur film in its normal non-conductive state, two electrodes mounted on said film and making electrical contact therewith, said electrodes being insulated from one another, means for establishing a potential difference between said electrodes whereby the impingement of said radioactive particles on said sulfur film places said film in a conductive state and means for measuring current flowing between the electrodes.

2. Apparatus for the detection of radioactive particles which comprises, in combination, a polycrystalline sulfur film in its normal non-conductive state, two electrodes mounted on opposite sides of said sulfur film and making electrical contact therewith, means for establishing a potential difference between said electrodes whereby the impingement of said radioactive particles on said sulfur film causes said film to become conductive and means for measuring current flowing between the electrodes.

3. Apparatus for the detection of radioactive particles which comprises, in combination, a polycrystalline sulfur film, two electrodes mounted on one side of said sulfur film and making electrical contact therewith, said electrodes being electrically insulated from one another and having interlocking finger-like lateral extensions, means for establishing a potential difference between said electrodes and means for measuring current flowing between the electrodes.

4. The apparatus of claim 3 wherein a luminescent material is mounted on said sulfur film.

5. Apparatus for the detection of alpha particles in the presence of strong fields of beta and gamma radiation which comprises, in combination, a polycrystalline film of sulfur between 20 and 40 microns in thickness, said sulfur film being in its normal non-conductive state, a first electrode making electrical contact with said sulfur film, a second electrode making electrical contact with said sulfur film, said first and second electrodes being insulated from one another, means for applying a potential difference between said electrodes whereby impingement of said radioactive particles on said sulfur film causes said film to become electrically conductive and means for measuring current flowing between said electrodes.

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Sept. 12 1961 C. F. GREEN 2,999,933

RADIATION RESPONSIVE MEANS

Filed Nov. 29, 1939

Fig. 1.

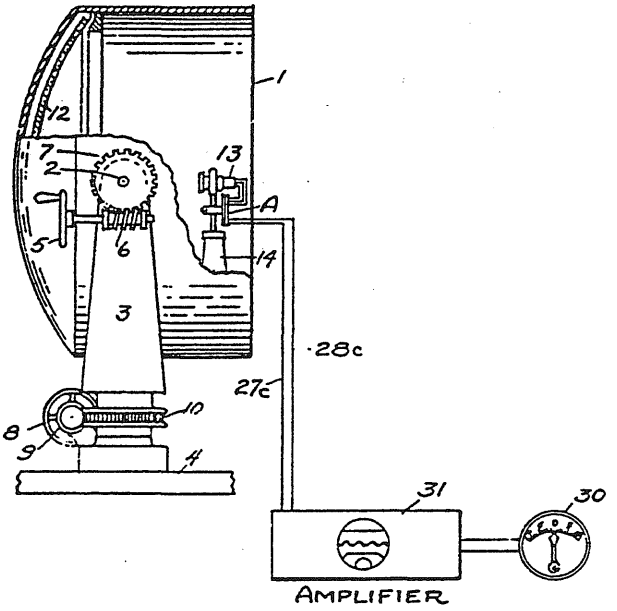


Fig. 2.

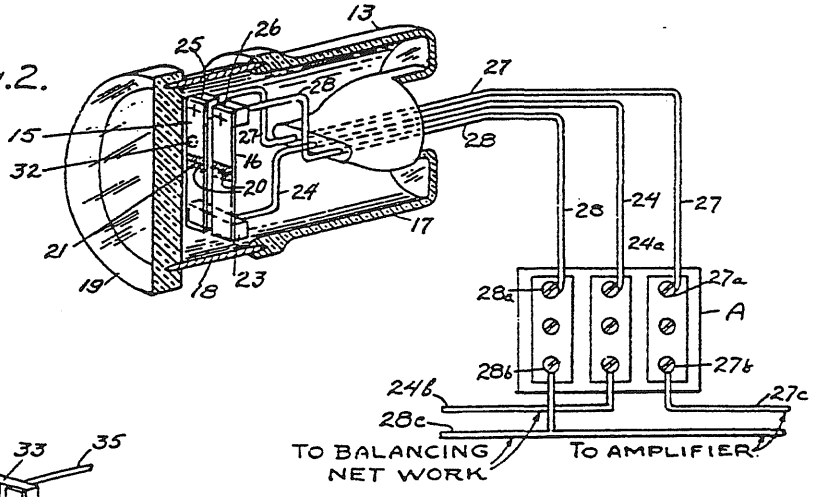
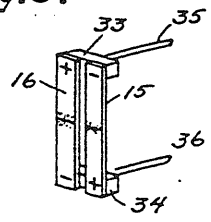


Fig. 3.



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By Thomas H. Green
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United States Patent Office 2,999,933 Patented Sept. 12, 1961

2,999,933

RADIATION RESPONSIVE MEANS

Charles F. Green, Schenectady, N.Y., assignor, by mesne assignments, to the United States of America as represented by the Secretary of War

Filed Nov. 29, 1939, Ser. No. 306,753
2 Claims. (Cl. 250—83.3)

This invention relates to apparatus for detecting distant objects by means of the thermal radiation from such objects and more particularly it is directed to a thermal-responsive detecting apparatus including an evacuated tube containing thermo-electric generating units by means of which distant invisible objects may be detected by their heat radiation.

Investigators in this particular field of research have experienced considerable difficulty in obtaining reliable indications with existing apparatus due to differences in the radiation received from different portions of the medium constituting the surrounding field or background of the object. For example, when searching the sky for an airplane which may be invisible, changes in radiation received from different portions of the sky and other changes in radiation such as those due to the effect of clouds have produced indications which have been confused with those due to the radiation from the object sought.

It is therefore one of the objects of this invention to provide an improved thermal-responsive detecting apparatus which avoids the difficulty mentioned by utilizing a radiation receiving means including an evacuated tube containing dual thermo-electric generating units which are associated within the tube in such a manner that while the receiving means will be effective to detect the object sought, the necessary compensation for variations in background radiation will be automatically made to render the indications of the apparatus independent of changes in background.

Another object of this invention is to provide a thermal-responsive detecting apparatus embodying an evacuated glass envelope having a rock-salt window and containing a pair of thermo-junctions, the elements of the junctions being interconnected within the tube so as to afford automatic compensation for background variations.

Another object of this invention is to provide a detecting apparatus having a thermo-couple vacuum tube arranged in the focal region of a reflector, the thermo-tube containing a pair of aligned thermo-junctions connected within the tube to oppose each other, the thermo-couple vacuum tube being mounted in the drum so that the focal point of the reflector passes through the junction line of one of the junctions within said tube.

With these and other objects in view, this invention consists in certain details of construction, combination and arrangement of parts to be more particularly hereinafter described and claimed.

Referring more particularly to the accompanying drawings in which like parts are designated by similar reference characters:

FIG. 1 is a side elevation partly in section of apparatus illustrating one embodiment of the instant invention;

FIG. 2 is a sectionalized perspective of the rock-salt window vacuum tube and illustrating the arrangement of the thermal-couple units therein, and

FIG. 3 is a fragmentary detail of a modified form of the thermal-couple units and illustrating a modification in the electrical arrangement of said units.

In the illustrated embodiment characterizing this invention and with reference to FIG. 1, there is shown a drum 1 which is pivotally mounted at 2 on the arms of a yoke 3 for oscillation in a vertical plane. Yoke 3 is pivotally mounted on base 4 for oscillation in a horizontal plane. Suitable means are provided for moving the drum in each of the two planes whereby changes in elevation and azimuth are effected in the pointing of the drum. While such means may be either manual or power operated, the former is illustrated for the sake of simplicity; thus the handwheel 5 operates through the worm 6 and wormwheel 7 to move the drum in the vertical plane and the handwheel 8 operates through the worm 9 and wormwheel 10 to move the drum in the horizontal plane.

Within the drum is mounted the parabolic reflector 12 in the focal region of which is arranged the radiation responsive means contained within the envelope 13 which is supported from the drum by the pedestal 14. The radiation responsive means illustrated comprises the two similar thermo-junctions 15 and 16 which are mounted within and near one end of the evacuated envelope 13. This envelope is represented as comprising the glass portion 17 having the metallic end portion 18, which for example may be a silver sleeve, and the window or end plate 19 of a radiation transmitting material such as rock-salt. The sleeve has a thin tapering edge at both ends, the glass being fused over the inner end and the outer end being made vacuum tight with the window by a suitable seal such as silver chloride, which construction is described and claimed in the copending application of August, J. Kling, Serial No. 306,750, filed November 29, 1939, for Thermo-Couple Tube, now Patent No. 2,543,-369.

The two thermo-junctions comprise similar strips arranged adjacent and parallel to each other and each composed of two thermo-electrically dissimilar metals. These junction strips have been made by welding together thin plates of the desired materials at their edges and then rolling down the welded plates until they attain the desired thinness which is of the order of 6 to 10 millionths of an inch. Since the direction of the rolling has been transversely of the strip or in the direction of the junction line 20 the welded connection between the two metals is preserved even though the thickness of the resulting strip is reduced to only a few millionths of an inch. Various metals may be employed to form these thermo-junctions. Very successful results, however, have been obtained by employing for one element of the junction an alloy composed of nickel 44%, copper 55.5% and iron 0.5% commonly known as "Copnic," and for the other element an alloy composed of nickel 90% and chromium 10%, commonly known as "Chromel." Assuming that the apparatus is to be used for horizontal searching, that is, the drum and reflector are to be swung in azimuth at a given elevation, the two thermo-junction strips are arranged vertically as shown in FIG. 2. If the rate of heat transfer of one metal is the same as that of the other the junction line 20 will be arranged in the middle of each strip, otherwise the relative lengths of the two components of each strip will be proportioned to provide equal heat transfer to the two ends thereof. To increase the heating effect of the radiation at the vicinity of the junction lines a transverse black band may be painted or otherwise formed on each junction over the junction line as shown at 21.

The two similar thermo-junctions are connected to oppose each other. FIG. 2 shows, for example, the two negative ends of the junctions connected together by being secured to the bar 23 which is supported by the wire 24 and the two positive ends connected with the external circuit. These two ends are secured to the bars 25 and 26 which are supported by the wires 27 and 28 respectively, mounted in the stem of the envelope. The wires 24, 27 and 28 connect with 24*a*, 27*a* and 28*a* of terminal panel A. Terminals 27*b*—28*b* of this panel are connected via conductors 27*c*—28*c* with the input side of an amplifier 31, the output side of which is connected

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to a suitable indicator in the nature of milliammeter 30, as clearly shown in FIG. 1 of the drawing.

As pointed out above the two thermo-junctions are arranged in the focal region of the reflector, whereby an image of the field of observation, represented by the small dotted circle 32, is formed thereon, the two junctions being affected by different but adjacent portions of said field. With the above-described apparatus one is able to detect the presenec of an object in the field of view if the radiation received from the object is greater or less than that received from the remainder of the field or background for if the radiation image of the object falls on either junction strip the resulting change in temperature thereof will cause a deflection to be made by the indicator 30. If the image does not happen to fall on the junction line the operator by suitably changing the elevation of the drum may cause the image to fall directly on the junction line thereby giving a maximum reading. If the object is moving, for example an airplane, and the drum is held in a fixed position and directed toward a certain portion of the sky, an indication will be given when the image of the object passes one strip or the other. A similar effect will be produced if the drum is oscillated in a searching operation whereby the image of the object sought is caused to sweep past the one strip or the other.

As a result of the connection and arrangement of the thermo-junctions which has been shown and described above, whereby the two junctions are connected to oppose each other, compensation is atuomatically made for changes in the amount of radiation received from different portions of the sky or for changes in the amount of radiation received due to the effect of clouds or to other atmospheric conditions. Such changes in the background radiation affect both thermo-junctions equally for it will be seen that since the junctions are similar in construction and are similarly mounted, being exact duplicates, whereby the rate of heat transfer is the same for both and since they are connected to oppose each other the voltage due to background radiation of one neutralizes that of the other with the result that the indicator shows no deflection. A further result of the opposing arrangement of the two thermo-junctions is that the direction of the deflection of the indicator shows which of the two junctions is affected by the image of the object being sought. Preferably the thermo-junctions are so mounted in the drum that the focal point of the reflector and hence the axis thereof, passes through the junction line 20 of one junction which junction will be used for the detection of radiating bodies while the other will serve to compensate for changes in background radiation. By means of well known apparatus, not shown on the drawing, including a suitable dial controlled by the position of the drum, the operator may read off the position of the radiating body in azimuth and in elevation when the meter reading is maximum. If the position of the body is changing in azimuth or elevation the operator by the proper manipulation of the hand wheels 8 and 5 while watching the indicator may keep the drum trained on the body.

Obviously the envelope 13 containing the thermo-junctions may be mounted in the drum with the junction strips arranged horizontally instead of vertically as shown, in which case the drum would be adapted to be swung in elevation rather than in azimuth in searching for radiating bodies.

To correct for any small differences in resistance in the thermo-junction that may occur in manufacture, a suitable network (not shown) may be connected between the terminals 24*a*—28*b* via the conductors 24*b*—28*c*, as shown in FIG. 2 of the drawings, whereby the two junctions may have equal resistances when exposed to equal amounts of radiation so that the pointer of the indicator will stand at zero.

In FIG. 2 the two thermo-junctions are shown connected in series with the external circuit. In the modified form illustrated by FIG. 3 the two junctions are shown connected together in parallel with the external circuit, the positive end of one junction being connected with the negative end of the other junction through the bars 33 and 34. The junctions are supported in the envelope and connected with the external circuit by the two wires 35 and 36 which correspond to wires 27—28 of FIG. 2.

In conclusion it will be apparent the instant invention provides a detecting apparatus which not only affords dependable indications without regard to background variations, but also, owing to the manner of interconnecting the junction strips within the tube, will materially increase the sensitivity of the apparatus.

Having described my invention, what I claim as new and wish to secure by Letters Patent is:

1. A detector comprising a high vacuum thermo-couple tube including a window transparent to thermal radiation, a pair of coplanar thermo-electric generating units arranged in side-by-side relation within said tube, the plane of said units being immediately to the rear of and parallel with the window of said tube, each unit being composed of a pair of vertically disposed narrow flat strips of electrically dissimilar conductors of an order of thinness within the range of 6 to 10 millionths of an inch, the strips of each unit being united to each other along a horizontally disposed junction line arranged intermediate of the strips and being coextensive with their widths, the junction lines of one pair of strips forming a continuation of the other pair of said strips, the respective units being electrically connected in opposition within said tube for automatically compensating for changes in background radiation.

2. An apparatus for detecting distant bodies by thermal radiation comprising means for collecting and bringing to a focus the thermal emanations from a distant body, means adjacent said focus for translating thermal to electrical energy and an electro-responsive indicating device in electrical relation with said last-mentioned means, said last-mentioned means comprising a highly evacuated tube provided with a window transparent to thermal radiation, a pair of coplanar thermo-electric generating units arranged in side-by-side relation within said tube, the plane of said units being immediately to the rear of and parallel with the window of said tube, each unit being composed of a pair of vertically disposed narrow flat strips of electrically dissimilar conductors of an order of thinness within the range of 6 to 10 millionths of an inch, the strips of each unit being united to each other along a horizontally disposed junction line arranged intermediate of the strips and being coextensive with their widths, the junction lines of one pair of strips forming a continuation of the other pair of said strips, the respective units being electrically connected in opposition within said tube for automatically compensating for changes in background radiation.

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Sept. 12, 1961 L. A. TAYLOR 2,999,934

RADIATION DETECTOR APPARATUS

Filed Nov. 29, 1939

Fig. 1.

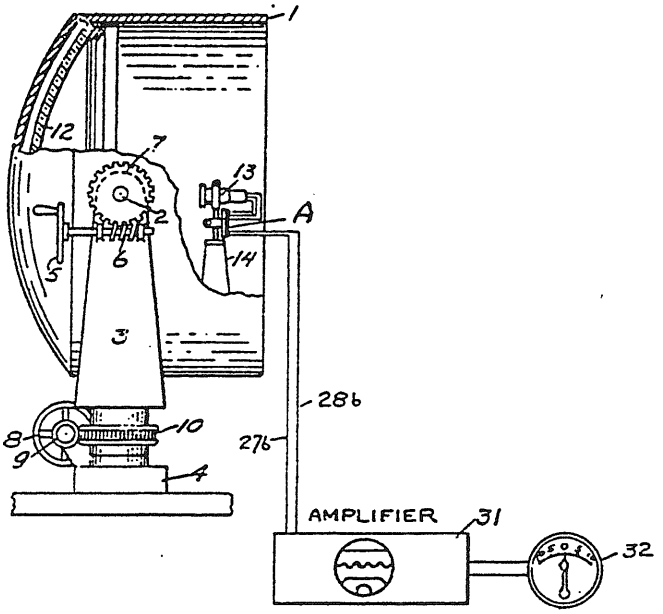


Fig. 2.

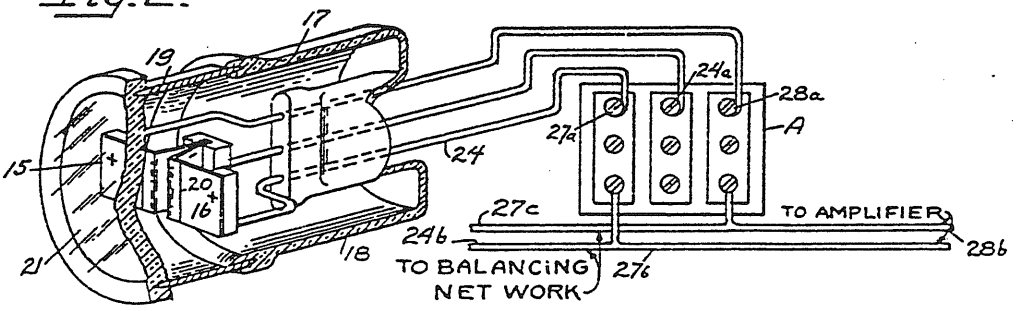


Fig. 3.

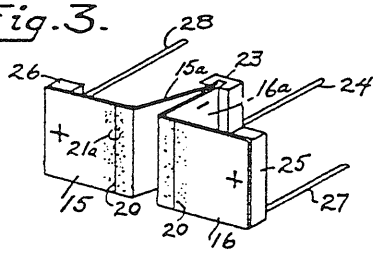
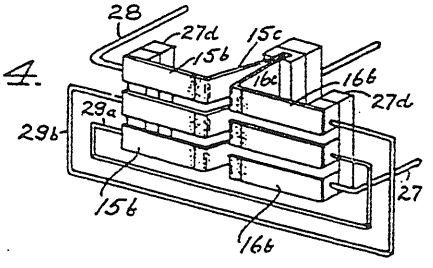


Fig. 4.



Inventor
Laurens A. Taylor
By Thomas D. Green.
Attorney

United States Patent Office 2,999,934 Patented Sept. 12, 1961

2,999,934

RADIATION DETECTOR APPARATUS

Laurens A. Taylor, Schenectady, N.Y., assignor, by mesne assignments, to the United States of America as represented by the Secretary of War

Filed Nov. 29, 1939, Ser. No. 306,755
7 Claims. (Cl. 250—83.3)

This invention relates to thermo-responsive devices for locating distant objects by thermo-radiation and it constitutes a further development of the apparatus for detecting distant objects by heat radiation described and claimed in the copending application of Charles F. Green, filed November 29, 1939, Serial No. 306,753.

One object of this invention is to provide a thermo-responsive detector adapted to be used in connection with collector-thermo-couple-amplifier-indicator systems, which will materially facilitate the detection of distant objects by said systems, owing to its simplicity and rapidity in response and angle of pickup.

Another object of this invention is to provide a thermo-responsive detecting device of the character specified having a plurality of thermo-couple strips arranged and proportioned so that said device when used with a suitably dimensioned reflector will afford a wide vertical acceptance angle or spread, particularly useful in systematic searching for unseen targets.

Another object of this invention is to provide a detecting apparatus equipped with a thermo-responsive device in the nature of an evacuated tube provided with a window having a high transmission coefficient and containing a pair of suitably disposed thermo-couple strips, interconnected within the tube to afford "bucking" outputs, the respective length of the strips being such as to provide a vertical acceptance angle, suitable for systematic searching.

Another object of this invention is to provide a detecting apparatus, including a thermo-responsive detector in the nature of an evacuated tube having a rock-salt window and containing a pair of horizontal disposed thermo-couple strips folded within the tube to provide the requisite spacing for their vertically extending junction lines.

With these and other objects in view, this invention consists in certain novel details of construction, combination and arrangement of parts to be more particularly hereinafter described and claimed.

Referring more particularly to the accompanying drawings in which parts are designated by similar reference characters:

FIG. 1 is a sectionized diagrammatic view of a collector-thermo-couple-amplifier-indicator system illustrating one embodiment of the instant invention;

FIG. 2 is a sectionized perspective view of the thermo-responsive detecting device adapted to be used in connection with the apparatus shown in FIG. 1, and illustrating the arrangement, mounting and connections of the thermo-couple strips within the tube;

FIG. 3 is a fragmentary detailed perspective of the thermo-couple strips within the detector tube; and

FIG. 4 is a perspective view of a modification of thermo-couple strips shown in FIGS. 2 and 3.

In the form of thermo-couple as described and claimed in the application of Charles F. Green, filed November 29, 1939, Serial No. 306,753, the junction strips are mounted side by side and connected in such a manner that their outputs are in "bucking" relation. While useful in background investigations, determination and comparison of ranges and characteristics of systems, this type of thermo-couple tube, owing to its limited "pickup" angle is not suited to systematic searching for distant targets. It is therefore the aim and purpose of the instant

invenion to provide a "line" thermo-couple tube having its thermo-couple strips arranged and proportioned to provide a "pickup" angle which will greatly facilitate systematic searching.

In the illustrated embodiment characterizing this invention a drum 1 is pivotally mounted at 2 between the arms of a yoke 3 which is swivelly supported on base 4. This arrangement permits vertical and horizontal oscillation of the drum as clearly shown in FIG. 1 of the drawings. Suitable means are provided for moving the drum in each of the two planes whereby changes in elevation and azimuth may be effected for the purpose of pointing the drum. While such means may be manual or power operated, the former is illustrated for the sake of simplicity; thus, the handwheel 5 operates through the worm 6 and worm-wheel 7 to move the drum in the vertical plane and the handwheel 8 functions through worm 9 and worm-wheel 10 to move the drum in the horizontal plane.

Within the drum is mounted the reflector 12 in the focal region of which is arranged a line thermo-couple tube 13, the tube being suitably supported on the upper end of a standard 14 as shown in FIG. 1 of the drawings. This device comprises two thermo-couple strips 15 and 16, which are in the present instance horizontally disposed and arranged in end to end relation with the junction lines 20 extending vertically, as clearly shown in FIG. 2 of the drawings.

The thermo-couple strips 15 and 16 are mounted within and near one end of an evacuated envelope 17. This envelope comprises a glass portion 18 having a metallic end portion 19, which in the present instance is a silver sleeve and a window or end plate 21 having a high transmission coefficient, such as rock-salt. The sleeve has a thin tapered edge at both ends, the glass being fused over the inner end, and the outer end of the sleeve is made vacuum tight with the rock-salt window by a suitable seal such as silver chloride, which construction is described and claimed in the copending application of August J. Kling, filed November 29, 1939, Serial No. 305,750, now Patent No. 2,593,369.

Each of the thermo-couple strips 15 and 16 is composed of two thermo-electrically dissimilar metals welded together along the junction line 20. These thermo-couple strips have been made by welding together thin plates of the desired material at their edges and then rolling down the welded plates until they obtain the desired thinness, which is of the order of 6 to 10 millionths of an inch. Since the direction of the rolling is transversely of the strip, or in other words, in the direction of the junction line 20, the welded connection between the two metals is preserved even though the thickness of the resulting strip is reduced to a few millionths of an inch. Very successful results have been obtained by employing for one element of the thermo-couple strip an alloy composed of nickel 44%, copper 55.5% and iron 0.5%, commonly known as "Copnic," and for the other element of the thermo-couple strip an alloy composed of nickel 90% and chromium 10%, commonly known as "Chromel."

Assuming that the apparatus is to be used for horizontal searching, that is, the drum and reflector are to be swung in azimuth at a given elevation, the two thermo-couple strips 15 and 16 as previously stated are arranged horizontally in an end to end relation with the junction lines 20 extending vertically. The two junctions are connected in series and in a reverse manner, the two outer elements, which are of one polarity being secured to support bars 25 and 26, and the two inner or intermediate elements which are of the opposite polarity being secured to the intermediate bar 23.

With this type of thermo-couple strip the length of

each junction line 20 is from three to seven times the length of the junction line disclosed in the thermo-couple strips described and claimed in the hereinabove mentioned application of Charles F. Green. The width of each junction is therefore many times the diameter of the image represented, for example, by the dotted circle 21*a* of the radiating body. The lengths of the electrically dissimilar metals forming each thermo-couple strip are substantially equal, the exact lengths being such that the rates of heat conduction to the supporting bars, considering the heat conducting properties of the materials, are equal. The intermediate bar 23 is approximately twice the size of each of the outer bars 25 and 26, whereby it has approximately twice the heat capacity thereof. The junction line 20 is substantially in the middle of each strip, but in order to bring the two junction lines closer together the inner elements 15*a*—16*a* of the thermo-couple strips 15 and 16 are bent backward as shown in FIGS. 2, 3 and 4. By thus bringing the two junction lines 20 closer together, one junction can be made to respond to a background region of radiation which is closer to the body whose radiation effects the other junction. By connecting the thermo-couple strips so that they oppose each other, in so far as background radiation is concerned, the one thermo-junction will exactly balance the other and no indication will be given by the indicating meter, hereinafter to be referred to.

The two thermo-couple strips are mounted with the outer elements as well as the adjacent portions of the inner elements in the focal region of the reflector and are horizontally offset so that the focal point of the reflector falls on one junction line 20 at approximately the middle thereof. As shown in FIGS. 2 and 3, the inner bar 23 is connected to and supported by the wire 24 which extends through the stem of the tube to the exterior thereof and is connected to terminal 24*a* of the terminal block A. The outer bars 25 and 26 are affixed to and supported by the wires 27 and 28 which extend through the stem of the tube, as clearly shown in FIG. 2, and are connected to terminals 27*a* and 28*a* of terminal block A. These terminals 27*a* and 28*a* are connected via conductors 27*b*—28*b* with the input side of an amplifier 31. The output side of amplifier 31 is connected through suitable conductors to a milliammeter indicator 32, as shown in FIG. 2 of the drawings.

To correct for small differences in resistance in thermo-junction that may occur in manufacture, a balancing network (not shown) may be connected via conductors 24*b*—27*c* between terminals 27*a*—24*a*, whereby the two thermo-couple strips may have equal resistances when exposed to equal amounts of radiation, thus retaining the pointer of the indicator at zero.

The form of thermo-couple strip which is shown in FIGS. 2 and 3, and which is relatively wide, giving a relative long junction line 20 is equivalent to a number of narrower thermo-couple strips connected in parallel. In certain cases it may be desirable to employ a number of narrow thermo-couple strips and connect them in series relation. Such an arrangement is shown in FIG. 4, in which several narrow thermo-couple strips 15*b*—16*b* are supported by separate bars of which adjacent bars of one polarity are mounted upon the insulating supports 27*d*, as clearly shown in FIG. 4 of the drawings. The thermo-junction strips are suitably connected in series by the conductors 29*a*—29*b*. It has been found that for thermo-couple strips constructed of the same materials and having the same area, series or parallel connections will give equal power output, provided the load resistance is matched to the thermo-junction.

In conclusion, it will be seen that this invention presents a detecting apparatus, embodying a high vacuum "line" thermo-couple tube having a rock-salt window and containing a pair of thermo-couple junction strips, connected in "bucking" relation and folded in a manner to space the vertically extending junction lines, a distance which experience has demonstrated gives the most effective results, and that when this tube is mounted in the focal region of a suitably dimensioned reflector, and connected to an amplifier-indicator system, as shown in FIG. 1, there is provided a detecting apparatus which is sensitive over a long range, rapid in response and efficient in searching for unseen targets, owing to its relatively wide angle of pickup.

Having described my invention, what I claim as new and wish to secure by Letters Patent is:

1. In an apparatus for locating distant bodies by thermo-radiation, means for collecting and focusing the heat radiation from a distant body to form a thermal image thereof, means within the focal region of the collected heat radiation for translating thermal into electrical energy, said means including an evacuated vessel provided with a rock-salt window, thermo-responsive means within the vessel, said means being electrically connected in opposition to effect automatic compensation for changes in background radiation and including a pair of vertically extending laterally spaced thermal junction lines, the latter being such as to provide a relatively wide vertical acceptance angle, one of said thermal junction lines being positioned to receive the thermal image formed by said first-mentioned means and an indicating device in electrical relation with said thermo-responsive means.

2. In an apparatus for locating distant bodies by thermo-radiation, means for collecting and focusing the heat radiation from a distant body to form a thermal image thereof, means within the focal region of the collected heat radiation for translating thermal into electrical energy, said means including an evacuated vessel provided with a rock-salt window, thermo-responsive means within the vessel, said means including a pair of thermo-couple strips arranged in end to end relation and electrically connected in opposition to effect automatic compensation for changes in background radiation, each of said strips including a thermal junction line extending transversely of its length and coextensive with its width, the length of said coextensive line being such as to afford a relatively wide vertical acceptance angle, one of said thermal junction lines being positioned to receive the thermal image formed by said first-mentioned means and an electro-responsive indicator in electrical relation with the thermo-couple strips.

3. In an apparatus for locating distant bodies by thermo-radiation, means for collecting and focusing heat radiation from a distant body to form a thermal image thereof, means within the focal region of the collected heat radiation for translating thermal into electrical energy, said means including an evacuated vessel provided with a rock-salt window and containing a pair of thermo-couple strips of a predetermined order of thinness and electrically connected in opposition, to effect automatic compensation for changes in background radiation, each of said strips including a thermal junction line extending transversely thereof and being of a length to afford a wide vertical acceptance angle, one of said thermal junction lines being disposed to receive the thermal image formed by said first-mentioned means, and an electric-responsive indicator in electrical relation with thermo-couple strips.

4. In an apparatus for locating distant bodies by thermo-radiation, means for collecting and focusing the heat radiation from a distant body to form a thermal image thereof, means within the focal region of the collected heat radiation for translating thermal into electrical energy, said means including an evacuated vessel provided with a rock-salt window, thermo-responsive means within the vessel, said means embodying a pair of thermo-couple strips of a predetermined order of thinness arranged in end to end relation and electrically connected in opposition to effect automatic compensation for

changes in background radiation, each of said strips embodying a vertically disposed thermo-junction line coextensive with the width of the strip, the thermo-junction lines of the two strips being parallel and laterally spaced a predetermined distance, the length of said thermal junction lines being such as to afford a wide vertical acceptance angle, one of said thermal junction lines being disposed to receive the thermal image formed by said first-mentioned means, and an electro-responsive indicator in electrical relation to the thermo-couple strips.

5. In an apparatus for locating distant bodies by thermo-radiation, means for collecting and focusing the heat radiation from a distant body to form a thermal image thereof, means within the focal region of the collective heat radiation for translating thermal into electrical energy, said means including an evacuated vessel provided with a rock-salt window, thermo-responsive means within the vessel, said means including a pair of thermo-couple strips arranged in end to end relation, each strip being composed of electrically dissimilar alloys of a predetermined order of thinness united along a vertically disposed junction line coextensive with the width of the strip, said strips being electrically connected in opposition for effecting automatic compensation for changes in background radiation, one of said thermal junction lines being disposed to receive the thermal image formed by said first-mentioned means, the length of the respective junction lines being such as to afford a wide vertical acceptance angle, and an electro-responsive indicator in electrical relation with the thermo-couple strips.

6. In an apparatus for locating distant bodies by thermo-radiation, means for collecting and focusing heat radiation from a distant body to form a thermal image thereof, means within the focal region of the collected heat radiation for translating thermal into electrical energy, said means including an evacuated vessel provided with a rock-salt window, thermo-responsive means within the vessel, said means comprising a pair of thermo-couple strips arranged in end to end relation and electrically connected in opposition to effect automatic compensation for changes in background radiation, each of said strips being of a predetermined order of thinness and including a vertically disposed junction line coextensive with the width of the strip, the thermal junction line of one of said strips being disposed to receive the thermal image formed by said first-mentioned means, said strips being folded rearwardly within the tube to juxtaposition the junction lines, and an electro-responsive indicator in electrical relation with said thermo-couple strips.

7. In an apparatus for locating distant bodies by thermo-radiation, means for collecting and focusing heat radiation from a distant body to form a thermal image thereof, means within the focal region of the collected heat radiation for translating thermal into electrical energy, said means including an evacuated vessel having a window transparent to thermal radiation, a plurality of thermo-couple strips within the vessel and immediately to the rear of the window, said strips being arranged in end to end relation and electrically connected in opposition to effect automatic compensation for changes in background radiation, one of said thermal junction lines being disposed to receive the thermal image formed by said first-mentioned means, said strips being of a predetermined order of thinness and including parallel laterally spaced junction lines, the length of said lines being such as to afford a wide vertical acceptance angle, and an electro-responsive indicator in electrical relation with said thermo-couple strips.

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Sept. 15, 1959 R. P. MULLIGAN 2,904,691

AERIAL PROSPECTING

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Fig. 8.

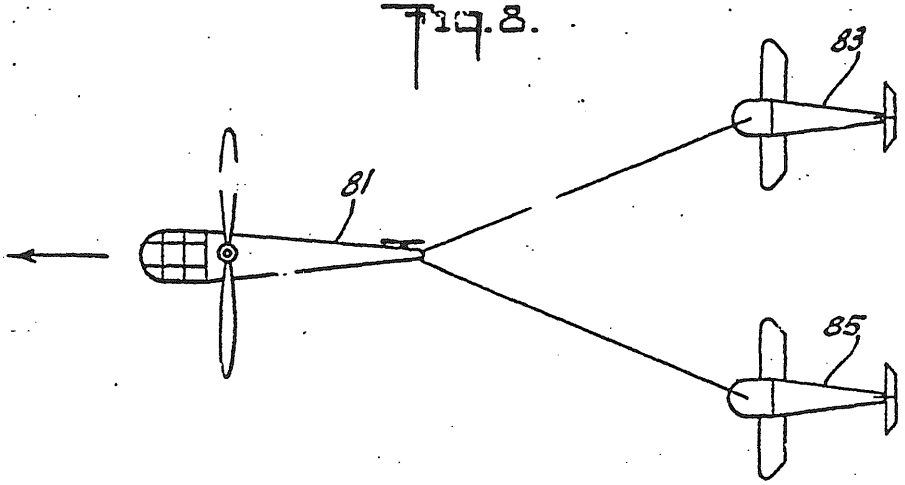


Fig. 9.

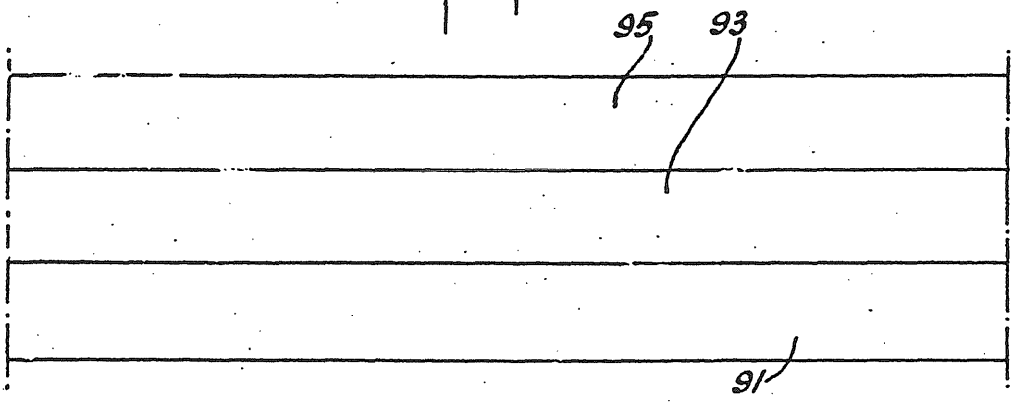
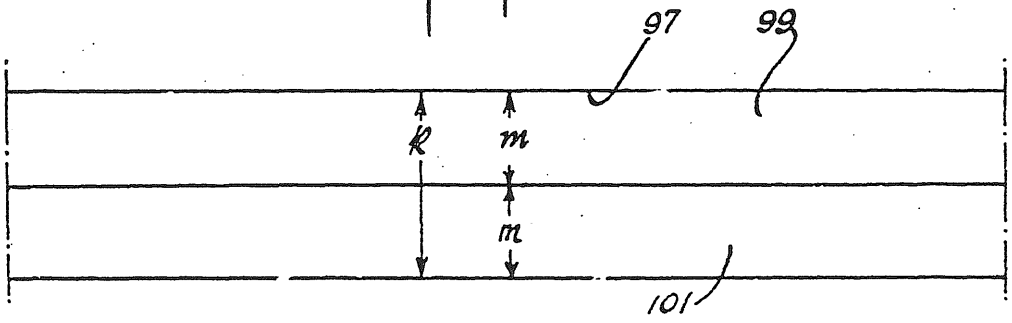


Fig. 10.



United States Patent Office 2,904,691 Patented Sept. 15, 1959

2,904,691

AERIAL PROSPECTING

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Application June 4, 1954, Serial No. 434,479

8 Claims. (Cl. 250—83.6)

The present invention relates to a novel method of prospecting for minerals by detecting radiation emanating from the ground, for example by detecting positive anomalies caused by gamma rays emanating from radioactive minerals such as uranium and radium ores, or by detecting negative anomalies caused by substantially non-radioactive ores such as iron, copper, lead, zinc and the like. More particularly, the invention is concerned with conducting radioactivity surveys from an aircraft such as a helicopter, fixed wing aeroplane, dirigible, glider or the like, which is flown rapidly over large areas of the earth.

Reference is made to U.S. Patent 2,562,914 for a thorough discussion of ore detection by positive and negative anomalies in measured radioactivity. Briefly, a positive anomaly is produced by ores having greater radioactivity than the surrounding country rock; and a negative anomaly is produced by ores having less radioactivity than the surrounding country rock.

Air-borne radioactivity prospecting has been employed heretofore by flying an aircraft across the surface of the earth while detecting radiation with a single radiation detector unit located within the aircraft. By such a procedure it has been possible to obtain an indication of the extent of mineral deposits within a relatively large area beneath the aircraft, for example a strip of the earth 150 feet wide being examined from a helicopter 150 feet above the earth. Since the ore body detected may lie at any point within the 150 foot width of the strip, its location by subsequent surveying on the surface of the earth has been difficult. The search may be narrowed by reducing the width of the flight lanes, but this requires considerably more traverses of the aircraft across the surface and obviously increases the expense and time for conducting a survey.

In accordance with the present invention the disadvantages of the prior art are successfully overcome by simultaneously flying at least two radiation detectors above the surface of the earth at positions spaced from one another, detecting radiation emanating from the earth with said detectors, recording measurements of the detected radiation, and comparing and correlating the measurements of detected radiation with one another and with the areas of the earth's surface "seen" by the respective detectors to determine the location of mineral bodies more exactly than has been possible heretofore.

In one embodiment of the method of the invention a self-propelled aircraft carrying a radiation detector is flown across the earth at one level while towing a second radiation detector at a lower level but in substantially the same vertical plane. Other embodiments involve flying more than two detectors at successively lower levels; and flying two or more detectors at positions spaced laterally from one another either in the same or different horizontal planes. If desired, the self-propelled aircraft need not carry a detector, in which case the two or more detectors are towed.

The principles of the invention will become apparent

from the following detailed description, having reference to the accompanying drawings wherein:

Fig. 1 is a schematic side elevational view showing how two radiation detectors are flown across the earth at different heights in the same vertical plane;

Fig. 2 is a schematic bird's eye view of a part of the earth's surface showing the location of different radioactive ore bodies as related to the flight path of the detectors shown in Fig. 1;

Fig. 3 is a reproduction of a radiation record showing the values of radioactivity measured and recorded by the two radiation detectors of Fig. 1, as related to the ore bodies and flight path shown in Fig. 2;

Fig. 4 is a perspective view showing schematically an arrangement of radiation detectors in a radiation detector unit;

Fig. 5 is a block diagram showing an arrangement of apparatus for measuring and recording detected radiation;

Fig. 6 is a side elevational view showing schematically how three radiation detectors are flown across the surface of the earth at different heights;

Fig. 7 is a plan view showing the positions of the areas of the earth's surface observed by each of the radiation detectors of Fig. 6;

Fig. 8 is a schematic plan view showing how a plurality of radiation detectors are flown across the surface of the earth in laterally spaced relationship to one another;

Fig. 9 is a plan view showing the positions of strips of the earth observed by appropriately collimated radiation detectors of Fig. 8; and

Fig. 10 is a plan view showing a modified arrangement of positions of strips of the earth which can be observed by appropriate collimation of the radiation detectors in Fig. 8.

As shown in Fig. 1 a self-propelled aircraft 11 carrying a radiation detector HD is flown across the surface of the earth at a selected height, such as 150 feet for example, while towing behind it on a cable 13 a streamlined glider 15 carrying a second radiation detector LD in substantially the same vertical plane but at a lower level such as 100 feet above the surface of the earth. The relationship between the positions of the aircrafts 11 and 15 is maintained substantially constant by means of adjustable vanes 17 and 19 on the glider 15.

The radiation detector HD at any given point in the survey observes a relatively large area 21 of the earth, while the detector LD observes a considerably smaller area 23. As the aircrafts fly along a straight flight path 24 these observed areas merge continuously to form long narrow lanes, as shown more in detail in Fig. 2.

In Fig. 2 the wide lane 25 of width a is observed by the radiation detector HD while the narrow lane 27 of width b is observed by the radiation detector LD. Both radiation detectors are arranged in the same vertical plane so that the narrow lane 27 is centered within the wide lane 25 and divides the latter into three narrow adjoining strips 27, 29 and 31.

One of the advantages of this novel procedure is that when the radiation detector HD provides an indication of an anomaly in the area of lane 25, the location of the ore producing this anomaly can be determined quite accurately by observing the measurement of radioactivity with the radiation detector LD. If LD shows an anomaly in radioactivity it indicates that the source is probably located within the narrow strip 27 rather than within either of the side strips 29 and 31. Conversely, when the detector LD shows relatively little evidence of an anomaly in radioactivity it indicates that the source must lie either in the strip 29 or the strip 31. Such indications make it possible for a ground party to locate

the ore much more quickly and economically than if the entire wide lane 25 had to be prospected on the ground, and more quickly and economically than if a series of separate aircraft flights had to be made along narrow lanes similar to 29, 27 and 31. Consequently, one flight across the surface of the earth accomplishes as much as three flights heretofore.

Another important advantage of the present invention is that it is possible to determine the general shape and extent of an ore body producing an anomaly. For example, referring to Figs. 2 and 3, ore bodies X, Y and Z are shown of different shapes and at different locations within th purview of radiation detector HD. If a single aircraft carrying only a single radiation detector unit were flown along the flight path 24 it would observe the relatively wide lane 25, and upon passing over each of the ore bodies X, Y and Z would detect their presence but not their precise location and shape. For example, as shown in Fig. 3 a strip chart 33 would bear a single trace HD' showing changes in radioactivity above the ore bodies, but the ore bodies could be in any part of the wide lane.

Interpretation is made much more accurate and complete by employing the second radiation detector LD at a lower level to show variations in radioactivity by the trace LD' on chart 33 as the detector passes above the ore bodies X, Y and Z.

Referring to Fig. 3 the change in radioactivity above the ore body X is recorded by a hump of magnitude *c* in the trace HD' whereas the trace LD' remains unchanged, thus indicating that the ore body X lies in either the strip 29 or 31 rather than in 27. Next, when the detectors pass above the ore body Y the trace HD' assumes a hump of magnitude *d* whereas the trace LD' assumes a hump of much greater magnitude *d'*, consequently showing that the ore body Y is located predominantly within the central lane 27 and is of a length corresponding to the length of the humps *d* and *d'*. Next, when the detectors fly above the large ore body Z both traces HD' and LD' exhibit humps of relatively great magnitudes *e* and *e'*, the magnitude of *e* being considerably greater than the magnitude of *d*, thus showing that the ore body at least extends along the entire width of the lane 25 and is of a length corresponding to the lengths of the humps *e* and *e'*.

It is evident that with detailed information of the type described above the work of the prospector is lightened greatly and the cost of prospecting for ores is greatly reduced.

For carrying out the method described above gamma ray radiation detector units of conventional types may be employed, for example, radiation detectors employing Geiger-Mueller tubes, or scintillation counters employing gamma ray sensitive crystals such as thallium-activated potassium iodide or calcium tungstate. Suitable detectors are described in U.S. Patents 2,397,071 and 2,486,94[illegible].

As is well known, due to air absorption effects involving different slant ranges and the inverse square law, these together involving an inverse fourth power function, a first uncollimated radiation detector at a lower altitude than a second higher uncollimated detector will have greater resolving power than the latter. In some cases, however, detectors are provided with collimating shields for greater discrimination.

Fig. 4 shows an example of a detector unit comprising a group of 6 individual detectors 35 connected in parallel to a preamplifier and mixer 37. A lead collimating shield 36 acts to define the width of the lane seen by the detectors. The particular detector unit shown is designed for location in a towed glider, and is connected to measuring and recording equipment in the self-propelled aircraft 11 by an electrical conduit 39 running along the towing cable 13.

Fig. 5 shows a typical arrangement of measuring and recording apparatus wherein a power supply 41 is connected to a high voltage transformer 43 which in turn is connected by conduits 45 and 47 to the radiation detectors HD and LD, respectively. Pulses from the two radiation detectors pass up cables 45 and 47 to a pair of rate meters 49 and 51, respectively, which in turn are connected to a dual pen recorder 53 which comprises two recording pens responsive to the counting rates from rate meters 49 and 51, and acting to draw two separate traces HD' and LD' on a strip of paper 33 to produce a record as shown in Fig. 3.

Fig. 6 shows a variant of the procedure wherein a self-propelled aircraft 61 tows two gliders 63 and 65 by means of cables 67 and 69 so that radiation is detected at three different levels above the earth's surface. Each of the aircrafts 61 and gliders 63 and 65 carries a radiation detector of the type described above and so connected as to produce three traces of radiation measurements.

The gliders 63 and 65 can be flown in the same vertical plane as the towing aircraft 61, or they can be spaced laterally from the aircraft 61 and from one another if desired.

Fig. 7 shows the arrangement of earth lanes observed by the three radiation detectors of Fig. 6 when flying in the same vertical plane, the detector of glider 65 observing a narrow path 71 of width *g*, the detector of glider 63 seeing a wider path 73 of width *h*, and the detector of aircraft 61 seeing a still wider path 75 of width *i*, all three of the lanes being symmetrical with respect to the flight path 77.

Fig. 8 shows a self-propelled aircraft 81 towing a pair of gliders 83 and 85 spaced laterally from the aircraft 81 and from each other. Each radiation detector unit located in these aircrafts sees a narrow lane of the earth's surface, and the construction of the detectors is such that all three of the lanes 91, 93 and 95 are contiguous to one another to provide in a single flight a sensitive and accurate representation of radioactivity from relatively narrow adjoining strips of the earth. To examine such equal widths of contiguous paths the gliders 83 and 85 should be flown at the same level as the aircraft 81.

Sometimes it is desirable to fly the aircraft at a high level and the towed laterally spaced gliders 83 and 85 at lower levels in such a way that the detector of aircraft 81 sees a relatively wide area 97 of the earth's surface of width *k* while each of the other radiation detectors sees contiguous strips 99 and 101 of the same width *m*, as shown in Fig. 10.

In airborne surveys conducted in accordance with the invention it is essential that the traces obtained, say those of Figs. 8 and 9, be correlated with the terrain over which the survey is made. This may be done in several ways.

One simple way is to provide an automatic time marker in the recorder, so that the time each portion of the trace is recorded is known. The operator of the detector notes the exact time that the aircraft is directly above prominent landmarks along the traverse, or above monuments or markers disposed on the ground along the traverse, and thus is able to correlate surface with trace by means of time.

Another but more complicated method is to employ a camera which is geared to the recorder of the detector. In this way a series of pictures of the underlying terrain is taken as the traverse is flown simultaneously with the recording of the trace of radiation intensity and correlated therewith.

Obviously, many modifications and variations of the invention, as hereinbefore set forth, may be made without departing from the spirit and scope thereof, and therefore only such limitations should be imposed as are indicated in the appended claims.

I claim:

1. A method of radioactivity aerial surveying com-

prising simultaneously flying at least two radiation detectors at different levels above the surface of the earth at positions spaced a substantial distance from one another, detecting gamma rays emanating from the earth with said detectors, recording measurements of the detected radiation, and correlating said measurements of detected radiation with one another and with the areas of the earth's surface seen by said detectors to detect anomalies and thereby determine the location of mineral bodies.

2. A method in accordance with claim 1, wherein said radiation detectors are spaced both laterally and vertically from one another.

3. A method in accordance with claim 1, wherein said radiation detectors are at different levels above the earth's surface, and fly in substantially the same vertical plane.

4. A method in accordance with claim 1, wherein said measurements are recorded on a single chart.

5. A method in accordance with claim 1 wherein one detector is carried by a self-propelled aircraft and wherein another detector is towed by said self-propelled aircraft and wherein said two detectors are flown at different levels above the earth's surface and substantially in the same vertical plane.

6. A method of radioactivity aerial surveying comprising simultaneously flying at least two radiation detectors above the surface of the earth at positions spaced a substantial distance from one another, said detectors being flown in substantially the same vertical plane, at least one of said detectors being flown at a lower altitude than another detector so that said lower detector is sensitive to a smaller portion of said area being surveyed than said higher detector, detecting gamma rays emanating from the earth with said detectors, recording measurements of the detected radiation, and correlating said measurements of detected radiation with one another and with the areas of the earth's surface seen by said detectors to detect anomalies and thereby determine the location of mineral bodies.

7. A method of radioactivity aerial surveying comprising flying a first radiation detector above the surface of the earth while detecting radiation emanating from the full width of a lane traversed by said aircraft and simultaneously flying a plurality of detectors at an altitude spaced a substantial distance below the altitude of said first detector and wherein the detectors flown at the lower altitude separately detect radiation emanating from narrow strips adjoining one another across the entire width of said lane.

8. The method of claim 7 wherein said first detector is carried by a self-propelled aircraft and said plurality of detectors are towed by the self-propelled aircraft.

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DIRECTIONAL RADIATION DETECTOR

Filed Dec. 23, 1953 3 Sheets-Sheet 1

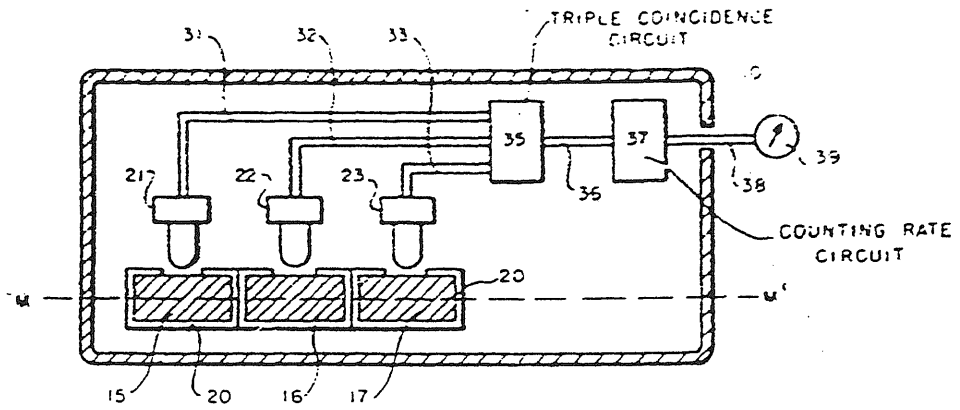

Fig. 1a

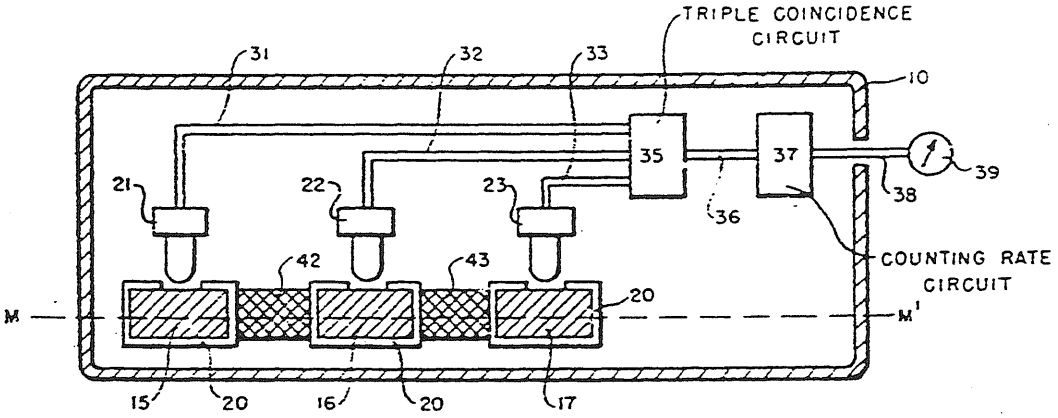

Fig. 1b

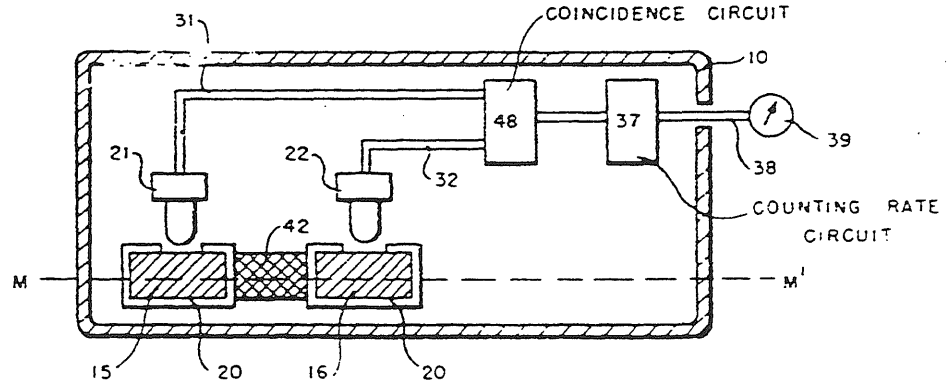

Fig. 1c

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DIRECTIONAL RADIATION DETECTOR

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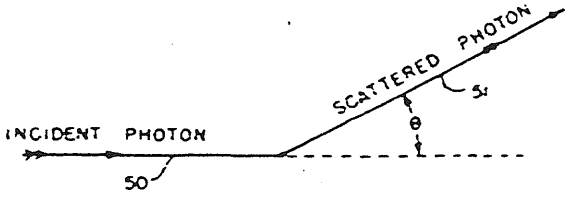

Fig. 2

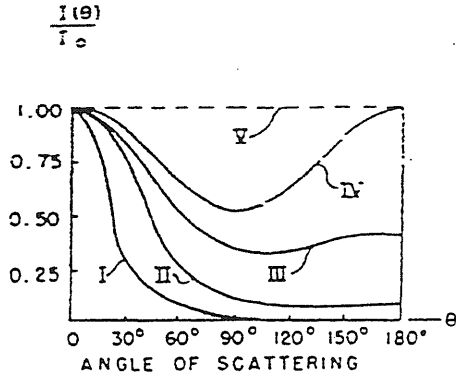

Fig. 4

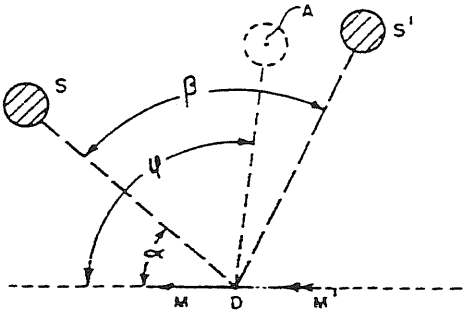

Fig. 5

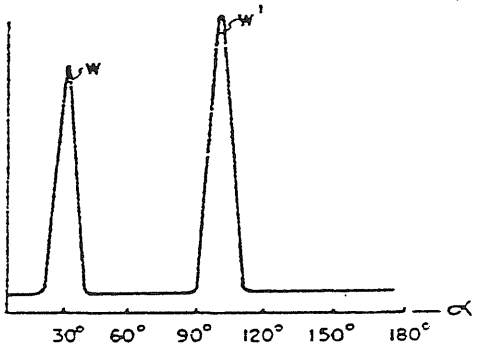

Fig. 7

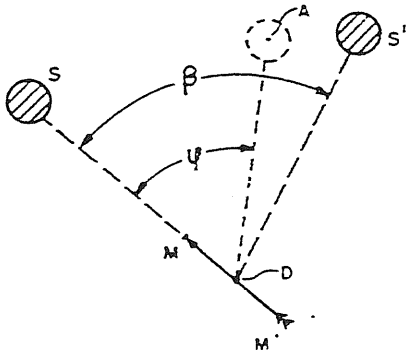

Fig. 6

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George A. Scherbatskoy

May 31, 1960 S A SCHERBATSKOY 2,939,010

DIRECTIONAL RADIATION DETECTOR

Filed Dec. 23, 1953 3 Sheets-Sheet 3

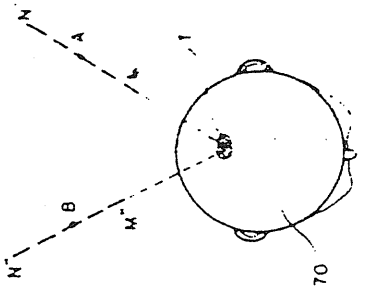

Fig. 8

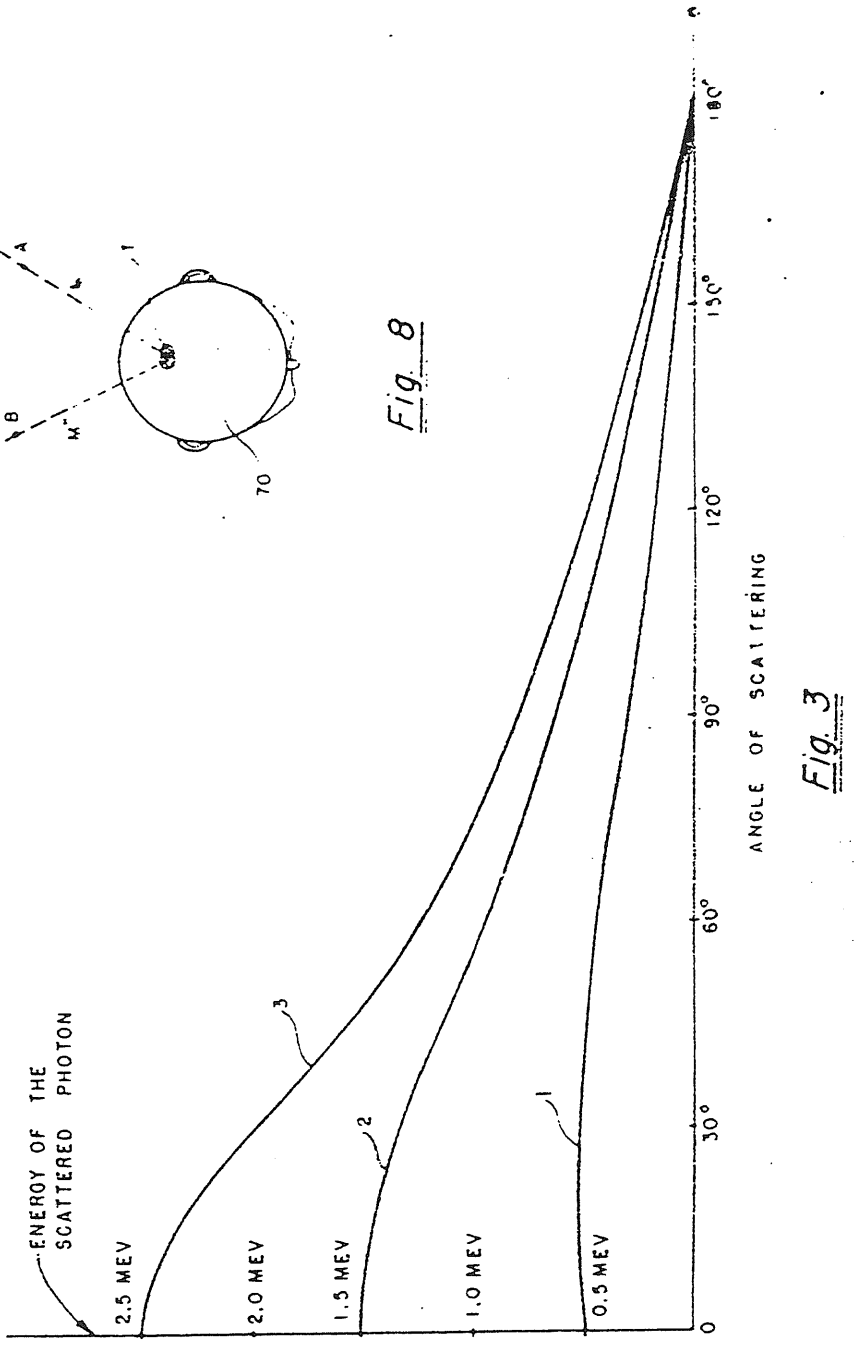

Fig. 3

INVENTOR.

Sage A. Scherbatskoy

United States Patent Office

2,939,010
Patented May 31, 1960

2,939,010

DIRECTIONAL RADIATION DETECTOR

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Filed Dec. 23, 1953, Ser. No. 399,972

3 Claims. (Cl. 250—71)

This invention deals with radiation measuring devices and has particular reference to a method and apparatus for determining the unknown direction and position of a source of nuclear radiation such as gamma rays.

Various methods and apparatus have been used in the prior art for determining the unknown position of sources, and were based essentially on the measurement of the intensity of radiation at various points in the space surrounding the source. Such methods lead, however, to very laborious measurements and computation and are not well adapted to the solution of the problem. Other methods have used a heavy lead shielding tube around the detector in order to give it some directional properties. These methods also have proved unsatisfactory because of the weight and bulk of the shielding tube.

The present invention is based on an entirely novel approach to the problem and provides a method and instrument for indicating the direction of an unknown source.

It is the object of this invention to provide an orientable detecting instrument that is adapted to be oriented in the direction of a source of gamma radiation.

It is another object of this invention to provide an instrument and method for determining direction and position of an unknown source of gamma radiation.

It is another object of this invention to provide a new method and instrument for locating tumors in the brain and other parts of the human body for diagnostic purposes.

It is another object of this invention to receive selectively hard gamma radiation that arrives at the detector and to eliminate from the reception soft gamma radiation.

It is another object of this invention to combine directional selectivity with the selectivity to hard gamma radiation.

Other objects of the present invention will be apparent from the description which follows when taken in connection with the drawing in which:

Fig. 1A shows a directional detector comprising three adjacent detecting elements aligned along a reference axis.

Fig. 1B shows a directional detector comprising three detecting elements aligned along a reference axis, said elements being separated one from the other by means of tungsten shields.

Fig. 1C shows a directional detector comprising two detecting elements aligned along a reference axis.

Fig. 2 illustrates certain angular relationships occurring during Compton scattering.

Fig. 3 shows energies of a scattered photon for various angles of scattering.

Fig. 4 shows angular intensity distribution of the scattered photons.

Fig. 5 shows a geometrical relationship between the direction of the detector axis and the direction of various sources in the surroundings.

Fig. 6 shows another geometrical relationship between

the direction of the detector axis and the direction of various sources in the surroundings.

Fig. 7 shows the output of the directional detector for various orientations of its axis.

Fig. 8 shows how the directional counter may be used for the location of brain tumors.

Referring now to Fig. 1A, the directional gamma ray detector shown therein is enclosed within a suitable container 10 and comprises as its essential elements three crystals 15, 16, 17 made of naphthalene, anthracene, sodium iodide, or any other suitable substance adapted to "scintillate," i.e. to produce a flash of light due to the excitation and ionization produced by the passage of a charged particle. The crystals 15, 16, 17 are aligned along a direction M—M' which we shall designate as "the axis of the directional detector" and each of these crystals has its outside surface covered with an aluminum reflector 20. The light flashes produced in the crystal 15 are adapted to be transmitted by means of the reflector 20 to a photomultiplier provided with a voltage supply, the combined photomultiplier and voltage supply being designated as 21. Similarly, the light flashes produced in the crystals 16 and 17 are adapted to be transmitted by means of the reflectors 20 to photomultipliers 22 and 23, respectively. Each of the photomultipliers is adapted to produce across its output terminals a current pulse in response to a flash of light in the corresponding crystal.

The outputs of the photomultipliers 21, 22, 23 are applied by means of leads 31, 32, 33, respectively, to a triple coincidence circuit 35. The coincidence circuit is adapted to produce across its output leads 36 an electric pulse whenever the pulses produced in the outputs of the photomultipliers 21, 22, and 23 occur in coincidence. Coincidence circuits are well known in the art and for their description see, for instance, E. Segre "Experimental Nuclear Physics," John Wiley & Sons, New York, N.Y. 1953, pp. 104–108.

The output leads of the coincidence circuit 35 are applied to a counting rate circuit 37. The counting rate circuit is of a standard construction and is adapted to produce across its output terminals 38 a D.C. voltage, the magnitude of which represents the frequency of impulses produced in the output leads of the coincidence circuit 35. The leads 38 are in turn connected to an indicator 39 indicating said output voltage.

Fig. 1B shows a modification of the arrangement of Fig. 1A in which the elements common to both figures are designated by the same numerals. It is noted that in Fig. 1B the crystals 15 and 16 are separated one from the other by a tungsten shield element 42 and the crystals 16 and 17 are separated by a tunsgten shield element 43.

Fig. 1C shows a modification of the arrangement of Fig. 1B that comprises only two crystals 15, 16 separated by the tungsten shield 42. The corresponding photomultipliers 21, 22 have their outputs connected to a double coincidence circuit 44. The output of the coincidence circuit 44 is connected to the counting rate circuit 37 and the output of said latter circuit is indicated on a meter 39.

We shall consider now the interaction of the incoming gamma radiation with crystals such as 15, 16, and 17. It is well known that gamma rays interact with matter in three different ways: by photoelectric effect, Compton effect, and pair formation. We shall consider here the first two types of interaction.

In the photoelectric effect which is characteristic of low energy photons, the incoming photon ejects an orbital electron from the atom of the crystal. The photon disappears in this process and the electron slows down in the crystal producing a pulse of light which in turn produces a current impulse in the output of the photomultiplier. Since the photon has entirely disappeared in the

crystal, no further effects are produced in any of the adjoining crystals shown in Figs. 1A, 1B, and 1C. Consequently, a photoelectric absorption is characterized by an occurrence of a pulse in one of the photomultipliers while the adjoining photomultipliers produce no pulse. Consequently, the photoelectric effect is not recorded, neither by the triple coincidence circuit 35 of Fig. 1A and Fig. 1B, nor by the double coincidence circuit 44 of Fig. 1C.

In the Compton effect the incoming photon is scattered by one of the electrons in the crystal. As a result of such scattering the electron has acquired kinetic energy, thus producing a pulse of light in the crystal, said light producing in turn a current impulse in the output of the photomultiplier associated with said crystal. The scattered photon usually escapes from the crystal and sometimes interacts with adjoining crystals, thus producing one or two coincident light pulses in said adjoining crystals. We shall investigate now when such an additional interaction does take or does not take place.

It is well known that as a result of Compton scattering the incoming gamma ray is usually deflected from its original course as a result of a collision with an electron. Such a deflection is shown in Fig. 2 in which 50 designates the photon trajectory before the collision. 51 designates its trajectory after the collision and θ is the angle of scattering which shows the deviation of the direction of the scattered photons from the direction of the incoming photons. The energy of the scattered photon is smaller than the energy of the incoming photon and depends upon the angle of scattering θ, i.e. the larger is the scattering angle, the smaller is the energy of the scattered photon. This relationship is shown diagrammatically in Fig. 3 in which curve 1 corresponds to an incident photon energy of 0.5 Mev. and curves 2 and 3 correspond to incident photon energies of 1.5 Mev. and 2.5 Mev., respectively. The abscissas represent the angles of the scattered photons and the ordinates are the energies of the corresponding scattered photon. It is seen that if the incident photon has relatively low energy (curve 1) the energy of the scattered photon decreases very slowly when the angle of scattering is increased. However, for incident photons of a relatively high energy such as 2.5 Mev. (curve 3) the energy of the scattered photons decrease rapidly when the angle of scattering is increased.

Fig. 3 does not describe fully Compton scattering since it shows merely how the energy of each individual scattered photon depends upon the angle of scattering and does not show the number of photons scattered into various angles. We need therefore an additional diagram such as shown in Fig. 4 showing the angular distribution of the intensity (i.e. number 2) of scattered photons. Curve I shows the angular distribution of the intensity of scattered photons when the initial photon energy is 2.5 Mev. Curves II and III show corresponding distribution for the initial photon energies of 0.5 Mev. and 0.08 Mev., respectively, and curve IV corresponds to very soft X-rays. The abscissas represent the angle of scattering θ; I_0 is the total incident flux and $I(\theta)\, d\Omega$ is the portion of flux that was scattered at an angle θ and is comprised within an elementary solid angle $d\Omega$. Consequently, the ordinates corresponding to the value $I(\theta)/I_0$ represent the distribution in intensity of the scattered flux for various values of θ. For further reference to this distribution see Heitler's "The Quantum Theory of Radiation," second edition, Oxford University Press, pp. 146–160 and particularly to Fig. 12, page 156.

When considering the angular distribution of scattered photons, we differentiate between "isotropic scattering" and "anisotropic scattering." In isotropic scattering, the intensity of the scattered radiation would be uniformly distributed in all directions and such a distribution would be represented by a horizontal line V. It is apparent from the curves I, II and III of Fig. 4 that the distribution of the scattered photons is not isotropic and tends to be concentrated at small values of the angle of scattering θ. Thus the photons are scattered in the forward direction and thus tendency for scattering forward becomes much more pronounced for incident photons of high energy. Thus curve IV showing the distribution for incoming photons of relatively small energy is not very different from the isotropic distribution represented by the curve V. We see, however, that for an incident photon energy of 0.5 Mev. (curve II), the scattering distribution is concentrated in the region of small values of θ (forward direction) and it becomes much more concentrated in the forward direction for incident photons of higher energies as shown by means of curve I (for 2.5 Mev.).

We shall utilize the above properties of Compton scattering to provide a radiation detection having the following two characteristics: (*a*) directional selectivity, and (*b*) energy selectivity. Because of its directional selectivity, the detector is adapted to respond primarily to radiations arriving from a predetermined direction and thus it can be used to determine the direction of an unknown source and for triangulation purposes to determine the position of an unknown source. Because of its energy selectivity, the detector is adapted to respond primarily to photons of large energy and is not responsive to soft photons. It is well known that the photons of low energy that arrive at the detector originate at the small distances in the immediate neighborhood of the detector while the photons of large energy that arrive at the detector have a considerably greater penetrating power and originate within large distances from the detector. Thus, because of its energy selectivity, the detector will be selectively responsive to radiation sources that may be located at considerable distances from the detector.

Consider now Fig. 5 showing the detector of the type illustrated in Fig. 1A positioned in the neighborhood of the point D, and having its axis aligned along the direction MM^1. Assume that the detector is submerged in a medium containing a distributed source of soft gamma rays and that a relatively large distance from the detector is located an unknown source S radiating gamma rays of relatively high energy. Let α designate the angle between the direction of the source S and the axis MM^1 of the detector. We shall show how the response of the detector will vary with the orientation of its axis, i.e. with the angle α. Assume also that another unknown source S^1 identical to the source S is located at a large distance from the detector and let β be the angle between the direction DS and DS^1.

Assume that the axis of the detector MM^1 is oriented in the direction of the source S as shown in Fig. 6. Then the gamma rays radiated by the source S arrive at the detector and interact with the crystal 15. Since the energy of the gamma rays is relatively high, we have here the case of Compton scattering illustrated by curve I of Fig. 4 according to which the scattered photons are concentrated in the forward direction. We may thus assume all the scattered photons went into the crystal 16 and a great portion of them undergoes a second scattering in the crystal 16. By referring now to curve 3 of Fig. 3, we see that the photons that have been scattered by the crystal 15 have a relatively high energy (since θ is small). Consequently, these photons undergo again a forward scattering by the crystal 16 into the crystal 17 and a great portion of these photons interact with the crystal 17, said last interaction being of the type of Compton scattering or photoelectric effect. It is well known that each interaction of a photon with a crystal knocks out an electron which in turn produces a flash of light in a manner well known in the art and causes an electric impulse to appear in the output of the corresponding photomultiplier. In this particular case a gamma ray arriving from the detector from the source S causes three successive interactions in the crystals 15, 16, and 17. These are almost simultaneous and therefore three impulses appear in the outputs of the photomultipliers 21, 22, and 23. These impulses ar-

rive in coincidence and therefore actuate the coincidence circuit 35. Thus a gamma ray arriving from the source S actuates the coincidence circuit and causes an impulse to appear across the output leads 36.

Consider now a photon radiated by the source S^1. This photon may interact with either of the crystals 15, 16, or 17. Since the incident photon has a high energy, we know from curve I of Fig. 4 that the scattered photon is projected forward in the same direction as the incident photon, i.e. in the direction S^1D. Such a scattered photon produced in either of crystals 15, 16, 17 escapes and does not interact with any of the adjoining crystals. In such case we obtain a single light pulse in the crystal in which the interaction took place, and a current impulse in the corresponding photomultiplier. Since there are no coincident impulses in the outputs of the adjoining photomultipliers, the coincidence circuit 35 remains inactive. Thus a gamma ray arriving from the source S^1 does not actuate the coincidence circuit and causes no impulse across the output leads 36.

Consider now the effect of the source that is continuously distributed throughout the medium surrounding the detector. Let the density of the distribution be such that the amount of radioactive substance contained in $cm.^3$ of the medium is small compared to the amount of the substance contained either in the sources S or S^1, but let the total amount of the radioactive substance uniformly distributed in said medium be considerably larger than the corresponding amounts contained in the sources S or S^1. Assume also that the substance continuously distributed in said medium emits hard and soft gamma radiation.

Thus in addition to gamma rays emitted by the sources S and S^1, the detector receives from all directions soft and hard gamma rays radiated by the continuously distributed sources, and the total amount of radiation received from the continuously distributed sources exceeds the radiation from sources S and S^1. It is apparent that a soft gamma ray interacts only with one of the crystals and the interaction is due to photoelectric effect. Consequently, for the reasons explained above, no coincidence pulses are produced. Therefore, the detector is insensitive to soft radiations.

Consider the hard radiations emitted from all directions by the surrounding medium. We shall determine first the effect of gamma rays radiated from a small volume of the medium enclosed in a small sphere surrounding the point A. The point A may be located anywhere in the space surrounding the detector. The gamma rays radiated by such a small sphere arrive at the detector at an angle φ, and said angle φ may have any value from 0° to 180°, depending upon the position of the point A. Consider now the effects of the scattering of these gamma rays by the crystal 15. Since the incident gamma rays have relatively large energies, the scattering is predominantly forward in accordance with curve I of Fig. 4. However, not all gamma rays are scattered forward and escape from the crystals. A relatively small portion of the incident flux is scattered at an angle $180°-\varphi$ into the crystal 16. These scattered photons may interact with the crystal 16. In such case we shall have two Compton interactions in a very rapid succession: the first produced by the incident photon in the crystal 15 and the second produced by the scattered photon in the crystal 16. We obtain, therefore, two coincident pulses in the outputs of the photomultipliers 21 and 22.

We have considered the fact that because of the shape of curve I of Fig. 4 the number of photons that arrived from the small sphere surrounding A and that have been scattered by the crystal 15 into the crystal 16 is relatively small, and therefore the number of coincident impulses at the outputs of the photomultipliers 21 and 22 is relatively small. If, however, we consider the effect not only of a small sphere in the medium but of the whole medium, it can be readily seen that the total number of photons that have been scattered by the crystal 15 into the crystal 16 is relatively large and, therefore, the number of double coincidences due to pulses at the photomultipliers 21 and 22 is large. We shall refer, however, now to curve 3 of Fig. 3 which shows that for an incident photon of high energy the scattered photon has very small energy if the angle of scattering is large. It is apparent that the photons that have been scattered by the crystal 15 into the crystal 16 have been deviated considerably from their original direction, i.e. the scattering angle was large. Consequently, the photons have small energies and when they interact with the crystal 16 they undergo a second scattering that is characterized by the curve IV of Fig. 4. Referring now more particularly to this curve, it is seen that for incident photons of small energy the scattering is more nearly isotropic, i.e. the scattered photon may be emitted in any direction, not necessarily forward. Consequently, the scattered photon that interacts with the crystal 16 may be scattered again, but not in the forward direction and thus may escape without producing any further interaction with the crystal 17. Since a further interaction with the crystal 17 is unlikely, we shall not obtain any pulse in the photomultiplier 23. Consequently, there is no occurrence of a triple coincidence, and the detector will not be responsive to the radiation emitted by the surrounding medium.

It is thus apparent that when the axis of the detector is directed towards the source S as shown in Fig. 6, the detector will be responsive only to the radiations emitted by S, i.e. it will be irresponsive to radiations emitted by the source S^1 and by the surrounding medium. Thus each pulse across the output leads 36 of the coincidence circuit will correspond to a gamma ray radiated by the source S. Consequently, the rate of arrival of such pulses determined by the output of the counting rate circuit 37 will represent the strength of the source S. Thus I have provided by means of the indicator 39 an index representing the strength of the source S.

If we rotate the detector by a small angle its response as shown by the meter 39 will decrease substantially to zero. However, when the axis of the detector becomes oriented towards the source S^1, the meter 39 will show the strength of radiation emitted by the source S^1 and will be still insensitive to any other radiations.

The present invention may be applied to those cases in which the location of a concentrated radiation source is unknown and it is desired to find the direction along which the source is located. The procedure consists in rotating the axis MM^1 of the directional counter until the indication of the meter 39 reaches the maximum value. The axis MM^1 will point then towards the source. A curve showing the variation in the output of the meter 39 with the rotation of the axis MM^1 is shown in Fig. 7. The peaks W and W^1 correspond to the angular position α and $\alpha+\beta$ of sources S and S^1, respectively (with respect to a reference direction shown in Fig. 5).

It is apparent that the above description relates to the radiation detector shown in Fig. 1A or to the one of Fig. 1B. The presence of tungsten in Fig 1B makes the directional counter more selective to hard gamma rays. The selectivity to hard gamma rays may also be increased by using four or more crystals arranged along the direction MM^1 and using a quadruple or quintuple coincidence circuit in place of the triple coincidence circuit 35.

It is also apparent that a counter comprising only two crystals such as 15, 16 aligned along the direction MM^1 can be used for the directional reception of gamma rays. When such detector as shown in Fig. 1C is directed towards the radiation source as shown in Fig. 6, the gamma rays arriving from the source S will be scattered by the crystal 15 into the crystal 16 and thus produce double coincidences, the frequency of said coincidences being indicated by the meter 39. The gamma rays that arrive from the source S^1 will be scattered by the crystal (either crystal 15 or 16) in the forward direction, and therefore will escape from the crystal and produce only

a single pulse. The influence of radiations uniformly distributed in the surrounding medium will depend upon the spectral composition of these radiations. If these radiations are soft, they produce photoelectric interaction either in the crystal 15 or in the crystal 16. We obtain thus single pulses without occurrence of coincidence, and therefore the detector remains insensitive to such radiation. If the gamma rays emitted by the medium are very energetic, then the scattering is predominantly forward. The detector will be insensitive to those radiations for the same reasons that it is insensitive to radiations from the source S^1 when the axis MM^1 is directed as shown in Fig. 5.

It is thus apparent that a detector such as shown in Fig. 1C responds to radiation sources such as S or S^1 only when its axis MM^1 is directed towards either of these sources. Furthermore, it has a relatively small response to the radiations emitted by the surrounding medium since it does not respond to those radiations emitted by said medium that are either very soft or very hard.

Fig. 8 shows an application of my invention for diagnostic purposes in medicine. It has been recently proposed to locate brain tumors by injection into the blood stream of a radioactive substance such as I^{131}-enriched diiodofluorescein. This substance is selectively absorbed by the diseased tissue and therefore after the injection the tumor becomes a source of radiation. The problem of locating the tumor becomes therefore identical with the location of a radiation source and can be solved by applying the principles of this invention. In Fig. 10, 70 indicates a human head and T the position of a tumor. The directional detector of Fig. 1 or of Fig. 7 is placed initially at the loaction A and rotated until its axis MS becomes aligned along .e direction N^1N^1. Subsequently we place the detector at the location B and rotate its axis MN until it becomes aligned along the direction $M^{11}N^{11}$. It is apparent that the intersection of the axis M^1N^1 with the axis $M^{11}N^{11}$ provides the position of the tumor T.

I claim:

1. A directional radiation detector characterized by selective response to hard gamma rays comprising a plurality of scintillating crystals, at least three in number, said crystals being mounted in alignment along a reference direction and spaced apart one from another, whereby a photon scattered in one of said crystals will produce no interactions in the others of said crystals unless its direction of arrival is along said reference direction and its scattering angle is small, each of said scintillating crystals being of the type which produces a flash of light responsively to the interaction of a gamma ray therewith, a photomultiplier tube for each of said scintillating crystals, said photomultipliers being operative to produce current impulses responsively to light flashes in the respective crystals therewith associated, a coincidence circuit connected to said photomultipliers for producing an output pulse whenever current impulses produced by said photomultipliers occur in substantial time coincidence, a counting-rate circuit connected to said coincidence circuit for producing a voltage representing the rate of occurrence of said output pulses, and means for indicating said voltage.

2. Apparatus according to claim 1 wherein a radiation-absorbing shield is interposed sandwich-fashion between each pair of said crystals along said reference direction, whereby substantially coincident flashes in said plurality of crystals occur only in response to gamma rays of very high energy arriving along said reference direction.

3. A radiation detector characterized by selective directional response to hard gamma rays comprising a plurality of scintillating crystals mounted in alignment along a reference direction and spaced apart one from another, a radiation-absorbing shield interposed sandwich-fashion between an adjacent pair of said crystals along said reference direction, a photomultiplier tube for each of said crystals, said photomultipliers being operative to produce current impulses responsively to light flashes in the respective crystals therewith associated, a coincidence circuit connected to said photomultipliers for producing an output pulse whenever current impulses produced by said photomultipliers occur in substantial time coincidence, a counting-rate circuit fed by said coincidence circuit for producing a voltage representing the rate of occurrence of said output pulses, and means for indicating said voltage, said apparatus being unresponsive to all radiation impinging on it save high-energy gamma rays arriving along said reference direction.

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May 31, 1966 A. H. YOUMANS 3,254,217

SCINTILLATION COUNTER FOR NEUTRONS AND GAMMA RAYS

Filed Dec. 14, 1950 2 Sheets-Sheet 1

Fig. 1

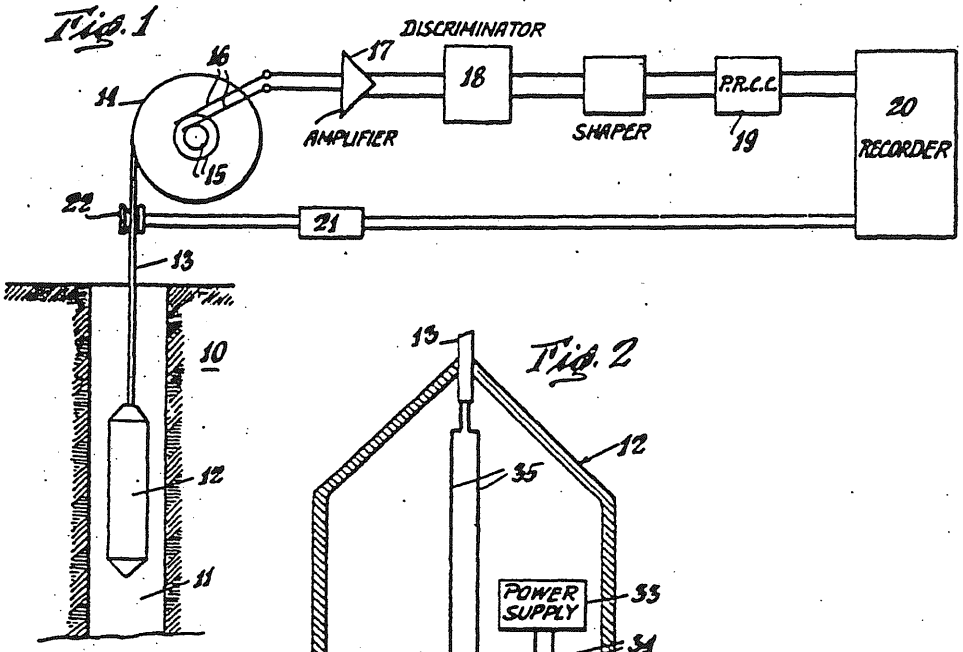


Fig. 2

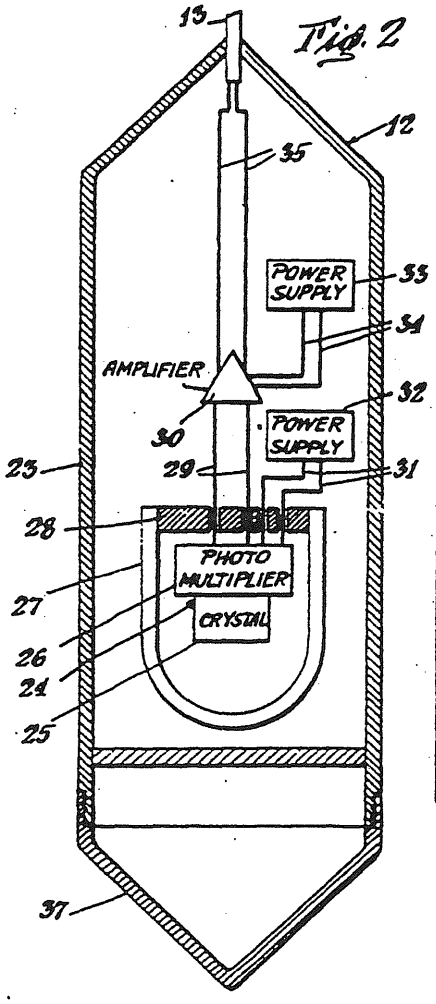
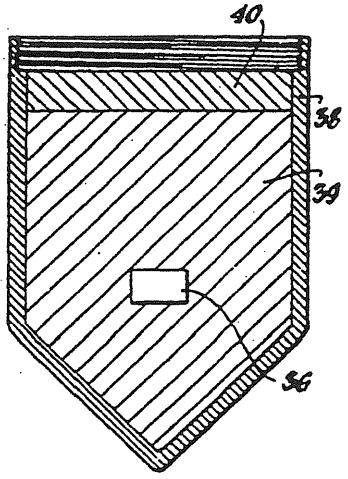


Fig. 3



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SCINTILLATION COUNTER FOR NEUTRONS AND GAMMA RAYS

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Fig. 4

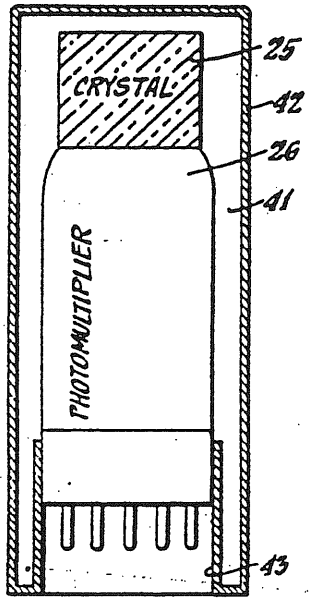


Fig. 5

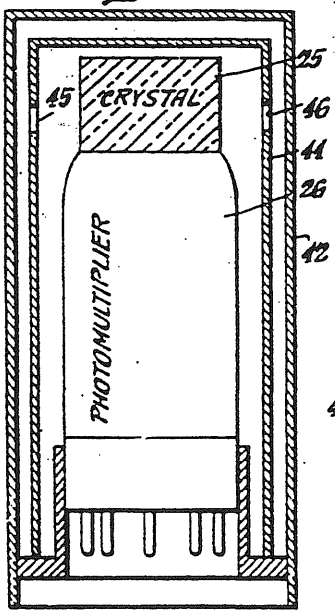


Fig. 6

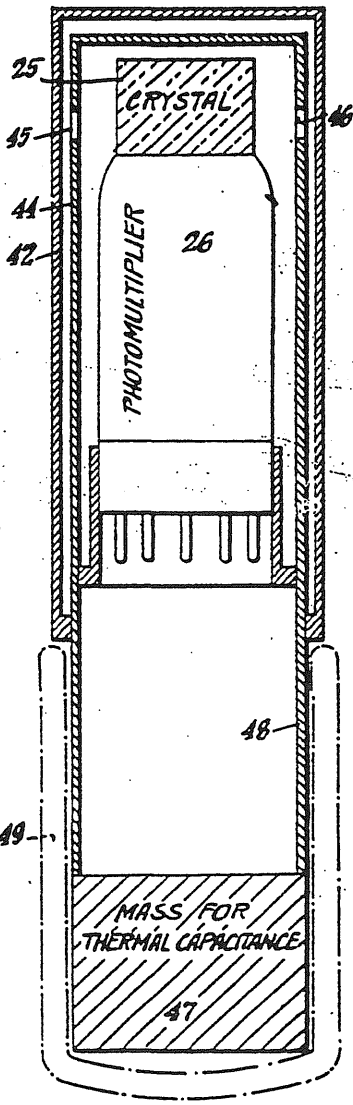
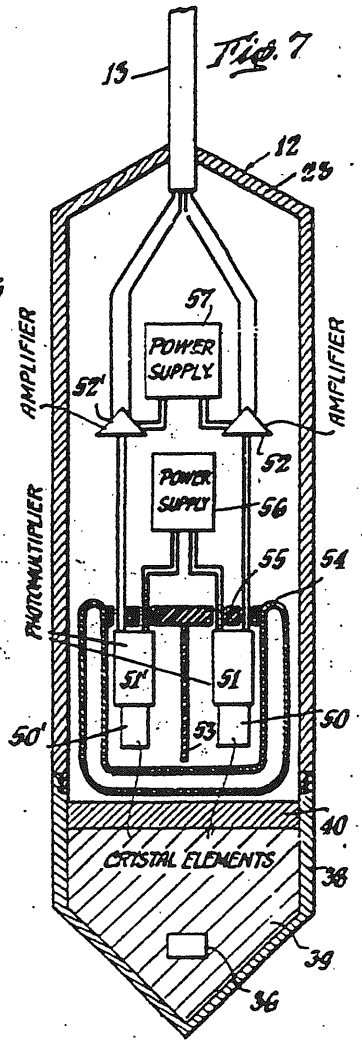


Fig. 7



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United States Patent Office 3,254,217 Patented May 31, 1966

3,254,217

SCINTILLATION COUNTER FOR NEUTRONS AND GAMMA RAYS

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10 Claims. (Cl. 250—71.5)

This invention relates to the art of geophysical prospecting and more particularly to the art of radioactivity well logging wherein scintillation counters comprising fluorescent media in conjunction with photomultipliers are used to detect radiation.

It is old in the art to log oil wells by measuring the natural radioactivity of the strata or by irradiating the strata adjacent the drill hole with fast neutrons or penetrating gamma radiation and simultaneously traversing the well with a gamma ray or neutron detector or both. Such detectors have been of the type which employs a gaseous ionizable medium and produces electrical pulses or continuous current. More recently a detector of relatively high efficiency has been found, the scintillation counter. Scintillation counters may have two types of fluorescent media, solid and liquid. Such media have certain advantages over a gaseous medium—their greater density permits a smaller size detector which is desirable in the small space available in a well logging instrument; their low resolving time permits high speed counting; their high efficiency provides a good signal-to-noise ratio; and their high stopping power is useful in gamma ray and high-energy particle detection. The scintillation counter has been well developed for laboratory use, but it is difficult to use in well logging since it involves the use of fluorescent media which operates less satisfactorily under the high ambient temperatures found in oil wells, and of photosensitive surfaces in photomultipliers which are subject to thermal deterioration at temperatures above 170° F. The temperatures encountered in deep wells may be as high as 400° F.

This invention comprises a scintillation counter adapted for use in radioactivity well logging. This counter may be used to detect neutrons or gamma rays or both. To protect the counter from excessive temperatures, insulation is needed around the counters. Whereas almost any insulating material may be used in the laboratory, the limits of space in a well surveying instrument that must go down a drill hole require that only the very best insulating material be used, i.e., a vacuum such as is provided by a Dewar flask.

Therefore, the primary object of this invention is to provide a method and apparatus for making a well log by detecting radiation in the well with a scintillation counter. Another object is to adapt a scintillation counter comprising a crystal and photomultiplier to use in a drill hole of restricted lateral dimensions for detecting radiation. This invention also contemplates the use of scintillation counters which employ liquids or crystals as scintillating media in the subsurface apparatus used in well surveying. A still further object of this invention is to provide means for protecting a scintillation counter when used in a subsurface well surveying instrument from the effects of high temperatures which may be encountered in certain wells. Another object of this invention is to provide a method and apparatus for making a neutron log of a well by excluding signals produced by gamma radiation in the detector as well as other signals such as dark currents originating in the photomultiplier of the scintillation counter. Other objects and advantages of the present invention will become apparent from the following detailed description when considered with the accompanying drawings, in which:

FIGURE 1 is a diagrammatic illustration of a geophysical well logging operation;

FIGURE 2 is an enlarged vertical sectional view of one form of the subsurface instrument;

FIGURE 3 is an enlarged vertical sectional view of a radiation source sub-adapted to be attached to the bottom of the instrument shown in FIGURE 2;

FIGURE 4 is a vertical sectional view of a modified form of insulating means for scintillation counters;

FIGURE 5 shows a further modification of the insulating means;

FIGURE 6 shows still another modification of insulating means which utilizes a thermal capacitance; and

FIGURE 7 is an enlarged vertical sectional view of a modified form of subsurface instrument in which two detectors are used.

In the art of radioactivity well logging, certain logs are made by measuring the gamma radiation naturally emitted by the well. The weakness of this radiation has heretofore made it necessary to use extremely complicated electrical circuits and bulky gaseous detectors in order to produce proportionally related electrical signals of sufficient intensity that they can be transmited to the surface and recorded. The scintillation counter is particularly adaptable for detecting natural radioactivity since it involves simpler circuits and provides a compact instrument of high efficiency and low resolving time. Other radioactivity logs are made by irradiating the formations adjacent the drill hole and detecting gamma radiation or neutrons influenced thereby. In FIGURE 1 of the drawings there is illustrated a well surveying operation in which any of these logs may be made.

A well 10 penetrates the earth's surface 11 and may or may not be cased. Disposed within the well is subsurface instrument 12 of the well logging system. Instrument 12 houses the scintillation counter. Cable 13 suspends the instrument in the well and electrically connects the instrument with the surface apparatus. The cable is wound on or unwound from drum 14 in raising and lowering instrument 12 to traverse the well. Through sliprings 15 and brushes 16 on the end of the drum, the cable is electrically connected to amplifier 17 which is in turn connected through pulse height discriminator 18 and pulse rate conversion circuit 19 to recorder 20. Recorder 20 is driven through a transmission 21 by measuring reel 22 over which cable 13 is drawn so that recorder 20 moves in correlation with depth as instrument 12 traverses the well.

Subsurface instrument 12 shown in FIGURE 1 may take the form illustrated diagrammatically in vertical section in FIGURE 2. The instrument as shown in FIGURE 2 is adapted for use in making a log of a drill hole by measuring the natural radioactivity emitted by the formations.

Instrument 12 comprises a housing 23 which encloses a scintillation counter 24. Scintillation counter 24 which comprises a fluorescent crystal 25 and a photomultiplier 26 may be suitably supported within a Dewar flask 27. The counter may be sealed in the Dewar flask by providing a closure member 28, formed of a suitable heat insulating material. Closure 28 is provided with suitable openings through which conductors may extend from the photomultiplier to a point outside of the Dewar flask enclosure. These conductors comprise conductors 29 which lead to amplifier 30 and conductors 31 which connect to a power supply illustrated schematically at 32. Amplifier 30 may be supplied with power from a second power supply indicated schematically at 33 through conductors 34. The output of amplifier 30 is connected by

suitable conductors 35 through a cable 13 to the recording equipment located on the surface of the earth.

Photomultiplier 26 although illustrated as a rectangle in the drawing is to be understood to include the necessary voltage divider and electric circuits for applying the required potentials to it. Additionally it is to be understood that the power supplies 32 and 33 may be replaced by suitable transformers and rectifiers which are supplied with power through the cable 13 from the surface of the earth.

In conducting a survey of a drill hole while using the apparatus illustrated in FIGURE 2, the instrument 12 is caused to traverse the formations penetrated by the well and in so doing radiation emitted by the formations, gamma radiation, impinges upon the crystal 25 of the scintillation counter. The crystal responds to the radiation by producing photons of light which are transmitted through the crystal to the photomultiplier 26. Photomultiplier 26 converts these photons of light into electrons which are multiplied in the multiplier section of the photomultiplier and the resulting current pulses are transmitted through conductors 29 to amplifier 30. The amplified pulses are then conducted via conductors 35 and cable 13 to the surface, where they are recorded in correlation with the depth at which they were produced.

Crystal 25 may be formed of materials such as cadmium tungstate, calcium tungstate, thallium activated sodium iodide (approximately 1 percent thallium) or thallium activated potassium iodide (approximately 1 percent thallium). These crystals when penetrated by radiation may produce Compton electrons, photoelectrons, or positron electron pairs which give up their energy in the production of photons of light.

As pointed out above certain liquids are adapted for use in scintillation counters. Such liquids are solutions of one percent anthracene dissolved in xylene and paradiphenylbenzene, terphenyl) dissolved in phenylcyclohexane or xylene. When using a liquid in place of the crystal 25, it is only necessary to replace the crystal with a suitable container filled with a scintillation liquid. In operation the liquid responds to radiation in a similar manner to that described in connection with the crystal and in the same fashion the resulting photons of light are transmitted to the photomultiplier, which produces pulses of current that may be amplified, transmitted to the surface, and recorded.

In the methods for detecting gamma rays described immediately above, the photons of light were produced in the scintillation media by the reaction of the gamma radiation with the atoms of the scintillation media. Gamma radiation can also be detected by enclosing the scintillation media within a material which reacts, when exposed to gamma radiation, to give up charged particles which, on entering the scintillation media, produce photons of light which are transmitted to the photomultiplier in the manner described above. The material within which the crystal is enclosed should be a heavy material such as lead or some other heavy metal. This crystal-enclosing metal may be formed about the crystal or may be a coating applied directly to the crystal. The thickness of the enclosing metal will be determined by the hardness of the gamma radiation that it is desired to detect. The detection process when using a crystal enclosed in a heavy metal involves the liberation of charged particles by the heavy metal when it is struck by gamma radiation. These charged particles enter the scintillation media and produce photons of light which are utilized as described above.

As shown in FIGURE 1 is is necessary to use a pulse height discriminator in conjunction with the scintillation counter recording system. Pulse height discriminator 18 functions to establish a threshold for determining which signals are transmitted to the recorder. Discriminator 18 may be regulated in a manner well-known in the art to pass to the recorder only pulses above a selected magnitude. The use of a discriminator is necessary

because the photomultiplier of the scintillation counter produces what are known in the art as "dark currents." These dark currents are evidenced by pulses of relatively small magnitude which may be blocked from the recorder by the discriminator.

In order to make a log which will be a continuous trace or curve drawn in correlation with the depth at which the radiation is detected, pulse rate conversion element 19 is interposed in the recording system of FIGURE 1. This element functions in a conventional manner, well-known in the art, to produce a direct current that varies in magnitude in accordance with the rate of occurrence of the pulses fed to it.

The instant invention as described thus far finds equal application in making well logs when using a source of radiation. In operation the subsurface device illustrated in FIGURE 2 may be modified to include a radiation source 36 by removing the bottom portion 37 of the housing thereof and replacing it with the sub shown in FIGURE 3 which carries the radiation source 36. If source 36 emits both neutrons and gamma rays and only neutrons are desired, then the sub shown in FIGURE 3 comprises the housing 38 which encloses a high density gamma ray absorber 39 in which is embedded a radiation source 36. It will be desirable to interpose between the radiation source and the detector a neutron absorbing shield. This may be located in the sub as indicated at 40 in FIGURE 3. If source 36 is a gamma ray source, absorber 39 is omitted and absorber shield 40 may be made of a high density material to stop direct passage of gamma rays from source to detector.

The apparatus resulting from the combination of the devices illustrated in FIGURES 2 and 3 is adapted for use in making a neutron-gamma ray log, that is a log which represents gamma radiation produced by neutron interactions in the formations. In this instance the source of radiation 36 would be one which emits neutrons. A gamma-gamma log, that is, one made by irradiating the formations with penetrating gamma radiations and detecting gamma radiations influenced by the formations, can also be made without modifying the detecting or recording system of the device. In this instance the radiation source 36 would be one which emits penetrating gamma radiations.

The scintillation counter is readily adapted to detect neutrons by replacing the scintillation medium used for the detection of gamma radiation by one which will respond to neutrons. Such a scintillation medium would be a crystal formed of a material such as cadmium tungstate, the neutron absorber being in this case cadmium; any other crystal having a material such as boron dispersed through it may alternatively be used: or the scintillation medium may be a liquid such as a solution consisting of xylene with one percent anthracene, having granulated Pyrex glass which is rich in boron dispersed therein.

Neutrons may also be detected by enclosing the scintillation medium disclosed for the detection of gamma radiation within a substance that will absorb the neutrons and in so doing emit radiation which will enter the scintillation media and produce measurable photons of light. When using a crystal this neutron reactive material may be formed about the crystal or made in the form of a coating for the crystal.

Such neutron reactive materials that are suitable for use as coatings for crystals are cadmium, boron, lithium, gadolinium, or uranium. The cadmium or gadolinium strongly absorbs slow neutrons and thereupon emits gamma radiation to which a scintillation medium will respond. Boron and lithium absorb slow neutrons and simultaneously emit alpha rays which will produce photons of light in the scintillation medium on entering it. Uranium may react with either slow or fast neutrons, depending on which of the isotopes is involved, and subse-

quently undergo fission. The high energy fission fragments and simultaneously emitted gamma and beta rays may react with the scintillation medium to produce photons of light. Fission results when the isotope U^{235} absorbs slow neutrons whereas fission of U^{238} results from capture of fast neutrons.

Obviously, when the coating material is opaque to the photons of light produced by radiation impinging upon the crystal a window must be provided in order for the photons of light to escape from the crystal and bombard the light-sensitive cathode element of the photomultiplier. It is to be understood that the scintillation medium may be in he form of a plurality of particles or be a single element of such geometry that a large portion of the crystal may be subjected to the neutron produced radiation. For example, when using a crystal such as calcium tungstate the scintillation medium may be formed from a plurality of elongated rod-like crystal elements having cross sectional dimensions such that they can be closely fitted together and disposed in such a manner that their axes extend toward the photocathode. The individual surfaces of these elements may be coated with the neutron reactive material.

When a liquid is used as a scintillation medium the container for the liquid may be formed of or coated with neutron reactive material. Such materials in this instance may be the same as those recited immediately above as suitable for coating materials for crystals.

The invention as described thus far has included means for protecting the scintillation counter against high temperatures which may be encountered in wells. In many shallow wells the variations in temperature are so slight that they produce no adverse effects and as a result the protective means for the scintillation counter may be omitted. However, in the majority of the wells, particularly the deep wells surveyed by the radioactivity logging method, temperatures are encountered which produce thermal deterioration of the photosensitive surfaces in the photomultiplier and lower the efficiency of some crystals as detectors of radiation to a point below that of the conventional detectors of the prior art, unless precautions are taken. The temperatures at which the photosensitive surfaces of the present commercially available photomultipliers will be subject to thermal deterioration are those above approximately 170° F. However, temperatures encountered in deep wells may be as high as 400° F. Under such conditions it is desirable to protect the scintillation counter by enclosing it in the most efficient heat insulating means permitted by the dimensions of the drill hole. To this end we have provided an evacuated spaced wall and jacket element which has been heretofore referred to in connection with the description of FIGURE 2 as a Dewar flask.

In FIGURE 4 there is illustrated a modified form of the invention in which the crystal 25 and photomultiplier tube 26 are enclosed in a hermetically sealed chamber 41. Chamber 41 is defined by an inner wall formed of the envelope of the photomultiplier tube 26 and the outer surface of the crystal element 25 and an outer wall in the form of a concentrically disposed outer cylindrical container 42 that is closed at one end. Container 42 has an inner annular element 43 of reduced diameter made integral with the open end thereof or secured thereto as by welding and which is adapted to engage the side wall of the base of the photomultiplier tube 26. A vacuum tight seal is formed between the base of tube 26 and the annular element 43. The chamber thus formed is then evacuated and sealed off. In order to further reduce transfer of heat to the crystal element 25 and photomultiplier tube 26 all surfaces presented to the chamber 41 may be silvered.

Another form of heat insulating means for the crystal 25 and photomultiplier tube 26 is shown in FIGURE 5. This form of the heat insulating means differs from that shown in FIGURE 4 in that a second cylindrical envelope 44 is concentrically disposed about the photomultiplier tube 26 and its associated crystal 25 but intervenes between the photomultiplier tube and its associated crystal and the container 42. By venting the container 44 as at 45 and 46, the evacuated region in FIGURE 5 is identical with that disclosed in connection with FIGURE 4. The intervening container 44, however, in the instant form of the invention provides an outer surface which may be silvered instead of applying the coating to the envelope of the photomultiplier tube 26 and those portions of the surfaces of crystal element 25 which are exposed to the evacuated chamber.

Still another form of insulating means for a scintillation counter is disclosed in FIGURE 6. This form of the invention differs from that disclosed in FIGURE 5 in that there is provided a relatively large thermal capacitance 47 which is arranged in thermal conductance with the guard formed by container 44. The thermal conductor connecting the container 44 with the thermal capacitance 47 may be an extension 48 of the container 44 which extends beyond the base of the photomultiplier tube and contacts the thermal capacitance 47. Thermal capacitance 47 may be a mass of water, ice, or other material of large thermal capacity. With this arrangement the rate of temperature rise of the photomultiplier assembly will be inversely proportional to the thermal capacity. It is evident that the photomultiplier tube will never become warmer than the enclosing container 44. Thermal capacitance 47 may be enclosed in a suitable heat insulating material, preferably disposed with a Dewar flask 49 which is illustrated in dotted lines in FIGURE 6. It is possible to dispense with the Dewar flask 49 by extending the outer housing 42 which surrounds the guard container 44 to enclose the entire thermal capacitance 47 and thereby provide a chamber which can be hermetically sealed, it being understood that hermetically sealed electrical lead through insulators will be provided through which electrical conductors would pass to make contact with the pins on the base of the photomultipler tube. It is obvious to those skilled in the art that other methods and apparatus may be employed for heat insulating the crystal element and its associated photomultiplier tube.

FIGURE 7 illustrates a subsurface instrument wherein a plurality of scintillation counters are used. Two such counters are shown comprising crystal elements 50 and 50', photomultipliers 51 and 51', and amplifiers 52 and 53. These counters may be arranged by suitable choice of crystals and/or suitable choice of coating material to be sensitive either to gamma rays or to both gamma rays and neutrons. Thus, to measure only neutrons with this combination element 50 may be cadmium tungstate and crystal element 50' may be calcium tungstate. Since the latter is not sensitive to neutrons, but both may be made equally sensitive to gamma radiation, the combination of the two measurements to yield their difference is indicative of neutron flux density. At the same time, the detection by crystal 50' and photomultiplier 51' indicates gamma ray flux density. The gamma rays thus detected may arise in the formations or they may be produced by neutron interaction in the cadmium tungstate crystal 25. The efficiency with which the combination can detect neutrons may be improved by interposing a gamma radiation absorber 53 between the two crystals or by arranging the geometry so as to make the radiation transfer a minimum.

As shown in FIGURE 7, the scintillation counters comprising the crystal elements 50 and 50' and photomultipliers 51 and 51' may be enclosed in an evacuated hermetically sealed heat insulating element 54 which may be a Dewar flask. Obviously, when such a container is used it would be provided with a closure element 55 that is provided with suitable electrical lead through insulators through which the electrical conductors may pass to the amplifiers 52 and 52' and to the power supply 56. A sec-

ond power supply 57 may be provided for the amplifiers 52 and 52'.

It is to be understood that this invention is not be limited to the specific modifications described but is to be limited only by the following claims.

I claim:

1. A method of radioactivity well-logging that comprises the steps of subjecting a scintillation counter that is sensitive to gamma radiation to gamma radiation within a drill hole while traversing the drill hole with the scintillation counter, simultaneously subjecting a second scintillation counter that is sensitive to both neutrons and gamma radiation to neutrons and gamma radiation while traversing the formations penetrated by the drill hole, electronically subtracting the signals produced in detecting gamma radiation by the first scintillation counter from the signals produced in detecting neutrons and gamma radiation by the second scintillation counter, and recording the resultant signals in correlation with the depth at which the detections occurred.

2. A method of radioactivity well-logging that comprises the steps of subjecting a scintillation counter that is sensitive to gamma radiation to gamma radiation within a drill hole while traversing the formations penetrated by the drill hole with the scintillation counter, simultaneously subjecting a second scintillation counter that is sensitive to both neutrons and gamma radiation to neutrons and gamma radiation while traversing the formations penetrated by the drill hole, maintaining the temperature of said scintillation counters substantially constant at a value below that which would impair their efficiency, electrically subtracting the signal produced by the first scintillation counter from that produced by the second scintillation counter, and recording the resultant signal in correlation with the depth in the drill hole at which detection occurred.

3. An apparatus for making a radioactivity log of a well that comprises in combination of subsurface instrument adapted to traverse a deep narrow well; means for traversing the well with said instrument; a crystal, that is adapted to scintillate when subject to penetrating radiation, confined within said instrument; a photomultiplier disposed adjacent said crystal and adapted to convert the scintillations of said crystal into electrical pulses; vacuum means for controlling the temperature of said crystal and photomultiplier; and means for measuring the electrical pulses as a measure of the penetrating radiations impinging upon said crystal.

4. An apparatus for making a radioactivity log of a well that comprises in combination a subsurface instrument adapted to traverse a deep narrow well; means for traversing the well with said instrument; a crystal, that is adapted to scintillate when subjected to penetrating radiation, confined within said instrument; a photomultiplier disposed adjacent said crystal and adapted to convert the scintillations of said crystal into electrical pulses; vacuum means for insulating said crystal and photomultiplier from heat encountered in the well; and means for measuring the electrical pulses as a measure of the penetrating radiations impinging upon said crystal.

5. An apparatus for making a radioactivity log of a well that comprises in combination a subsurface instrument adapted to transverse a deep narrow well; means for transversing the well with said instrument, a scintillation counter disposed within said subsurface instrument, a cylindrical jacket having a closure in one end thereof disposed about said scintillation counter and having its open end form a gas-tight seal with the base of said scintillation counter to define a concentric chamber about said scintillation counter that may be evacuated, a cylindrical guard element concentrically disposed between said first recited cylindrical element and said scintillation counter, said guard element being provided with vent orifices that are adapted to establish communication between the two concentric chambers formed by said guard element, means also disposed within said subsurface instrument for amplifying electrical pulses from said scintillation counter, means for transmitting the amplified pulses to the surface of the earth, and means for measuring a property of said pulses as an indication of the physical properties of the formations traversed.

6. An apparatus for making a radioactivity log of a well that comprises in combination a subsurface instrument adapted to traverse a deep narrow well; means for traversing the well with said instrument, a scintillation counter disposed within said subsurface instrument, a cylindrical jacket having a closure in one end thereof disposed about said scintillation counter and having its open end form a gas-tight seal with the base of said scintillation counter to define a concentric chamber about said scintillation counter that may be evacuated, a cylindrical guard element concentrically disposed between said first recited cylindrical element and said scintillation counter, said guard element being provided with vent orifices that are adapted to establish communication between the two concentric chambers formed by said guard element, said guard element extending at one end beyond the base of the scintillation counter, a thermal capacitance connected to the extended end of said guard element, means also disposed within said subsurface instrument for amplifying electrical pulses from said scintillation conuter, means for transmitting the amplified pulses to the surface of the earth, and means for measuring a property of said pulses as an indication of the physical properties of the formations traversed.

7. An apparatus for making a radioactivity log of a well that comprises in combination a subsurface instrument adapted to traverse a deep narrow well, means for traversing the well with said instrument, a scintillation counter disposed within said subsurface instrument, a cylindrical jacket having a closure in one end thereof disposed about said scintillation counter and having its open end form a gas-tight seal with the base of said scintillation counter to define a concentric chamber about said scintillation counter that may be evacuated, a cylindrical guard element concentrically disposed between said first recited cylindrical element and said scintillation counter, said guard element being provided with vent orifices that are adapted to establish communication between the two concentric chambers formed by said guard element, said guard element extending at one end beyond the base of the scintillation counter, a thermal capacitance connected to the extended end of said guard element, an evacuated spaced wall and jacket vessel disposed about the thermal capacitance and extended portion of said guard element, means also disposed within said subsurface instrument for amplifying electrical pulses from said scintillation conuter, means for transmitting the amplified pulses to the surface of the earth, and means for measuring a property of said pulses as an indication of the physical properties of the formations traversed.

8. An apparatus for making a radioactivity log of a well that comprises in combination a subsurface instrument that is adapted to traverse a deep narrow drill hole, means for traversing the drill hole with said instrument, a scintillation counter that is sensitive to gamma radiation disposed within said instrument, means for conducting electrical pulses produced by said scintillation counter when subjected to gamma radiation to the surface of the earth, a second scintillation counter that is sensitive to both neutrons and gamma radiation also disposed within said instrument, means for transmitting the electrical pulses produced by the second scintillation counter when subjected to neutrons and gamma radiation to the surface of the earth, means at the surface for receiving said electrical pulses, said means including electronic means for subtracting the signals produced by the first recited scintillation counter from the sig-

nal produced by the second recited scintillation counter, and means for recording the resultant signal in correlation with the depth of the drill hole at which the scintillation counters were subjected to radiation.

9. An apparatus for making a radioactivity log of a well that comprises in combination a subsurface instrument that is adapted to traverse a deep narrow drill hole, means for traversing the drill hole with said instrument, a scintillation counter that is sensitive to gamma radiation disposed within said instrument, a second scintillation counter that is sensitive to both neutrons and gamma radiation also disposed within said instrument, means for controlling the temperature of said scintillation counters, means for separately transmitting the electrical pulses produced by each scintillation counter when subjected to radiation to the surface of the earth, means at the surface for receiving said electrical pulses, said means including electronic means for subtracting the signals produced by the first recited scintillation counter from the signal produced by the second recited scintillation counter, and means for recording the resultant signal in correlation with the depth of the drill hole at which the scintillation counters were subjected to radiation.

10. An apparatus for making a radioactivity log of a well that comprises in combination a subsurface instrument that is adapted to traverse a deep narrow drill hole, means for traversing the drill hole with said instrument, a source of neutrons disposed within said instrument, a scintillation counter that is sensitive to gamma radiation disposed within said instrument, a second scintillation counter that is sensitive to both neutrons and gamma radiation also disposed within said instrument, means for controlling the temperature of said scintillation counters, means for separately transmitting

the electrical pulses produced by each scintillation counter when subjected to radiation to the surface of the earth, means at the surface for receiving said electrical pulses, said means including electronic means for subtracting the signals produced by the first recited scintillation counter from the signal produced by the second recited scintillation counter, and means for recording the resultant signal in correlation with the depth of the drill hole at which the scintillation counters were subjected to radiation.

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May 31, 1966 J. M. FINLAY ETAL 3,254,219

NUCLEAR BLAST DETECTOR AND ALARM SYSTEM

Filed Jan. 7, 1963 2 Sheets-Sheet 1

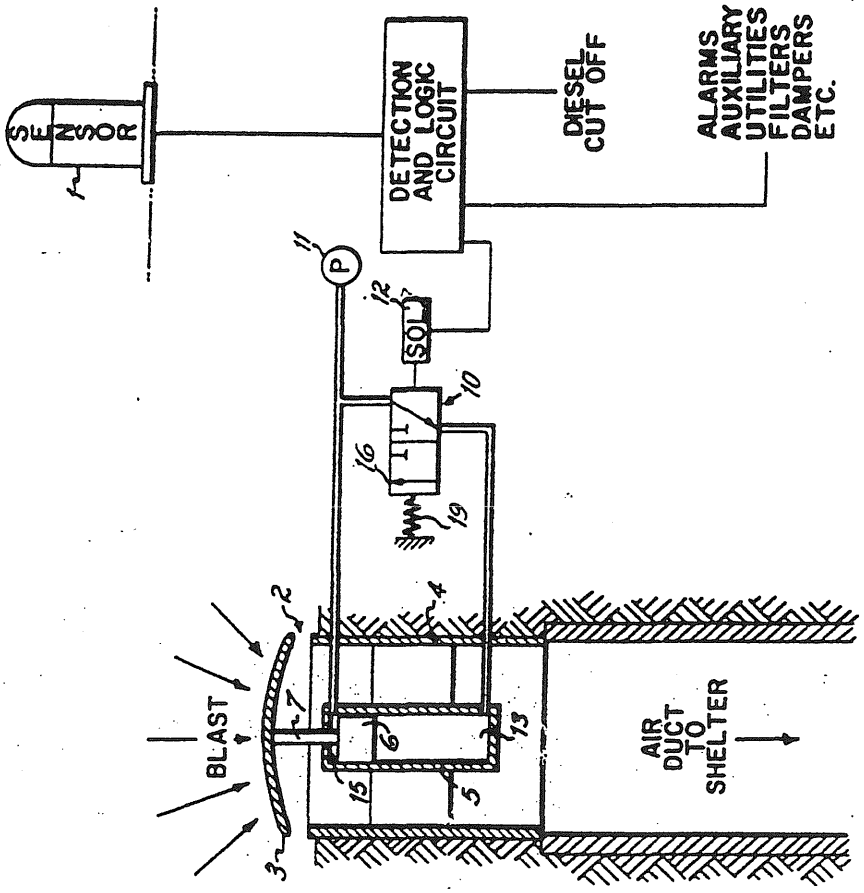

Fig. 2

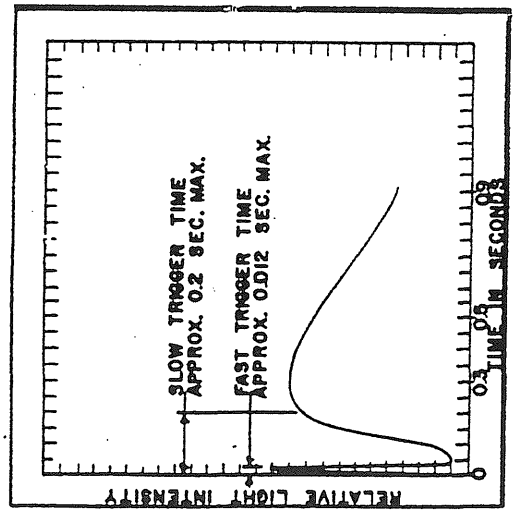

Fig. 1

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May 31, 1966 J. M. FINLAY ETAL 3,254,219

NUCLEAR BLAST DETECTOR AND ALARM SYSTEM

Filed Jan. 7, 1963 2 Sheets-Sheet 2

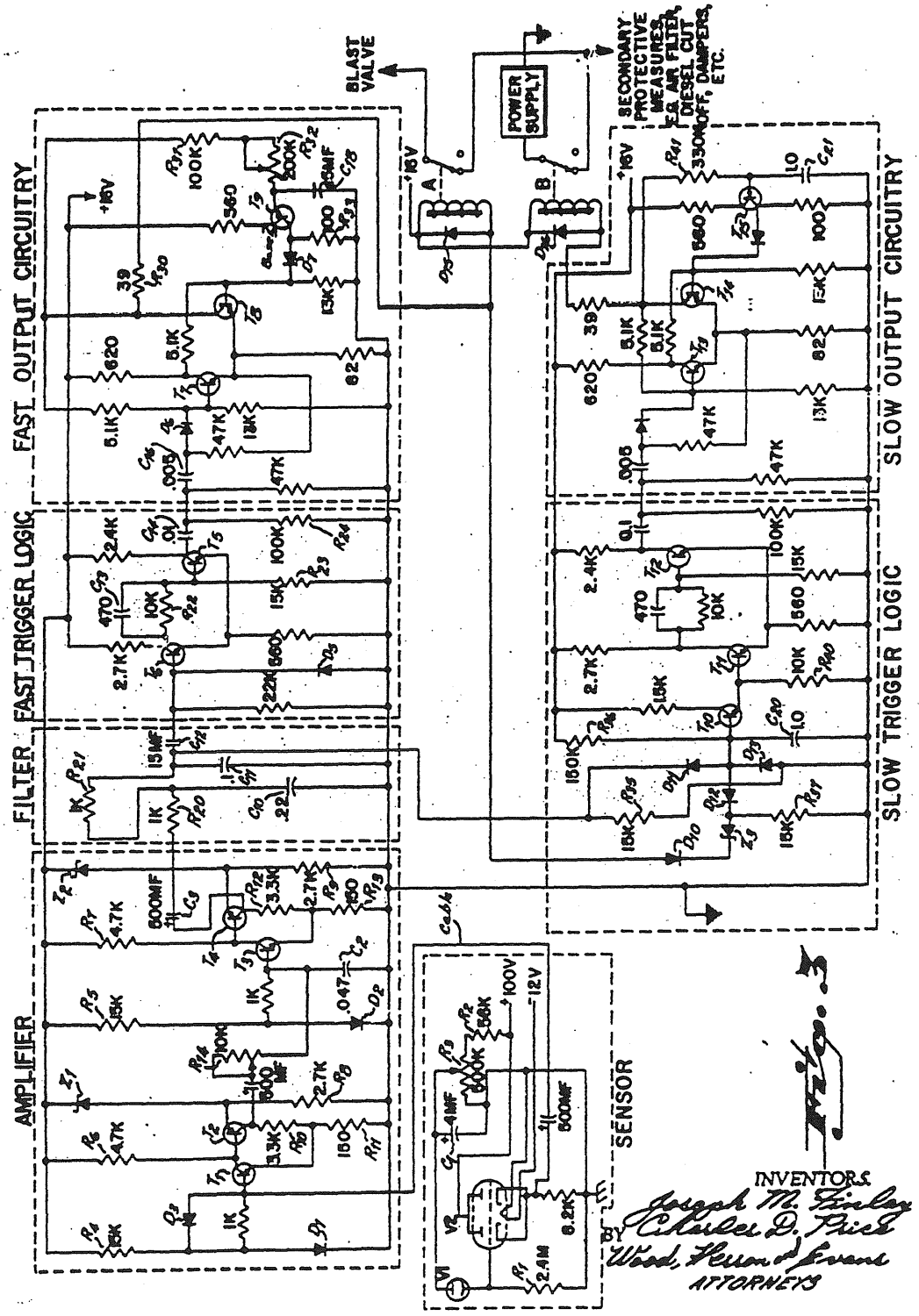

Fig. 3

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3,254,219
NUCLEAR BLAST DETECTOR AND ALARM SYSTEM

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This invention relates to a method and apparatus for detecting nuclear explosions and initiating protective measures.

In nuclear bomb shelter installations it is usually necessary to take last minute "button-up" precautions to prevent damage from near-miss nuclear explosions. Blast valves in the shelter air ducts must be closed to prevent the shock wave of the blast from entering the ducts. Diesel operated generators must be shut down when the closed blast valves cut off the external air supply, auxiliary utilities must be started in operation, dampers must be closed, air filters activated, alarms sounded, and other warning and protective devices must be actuated.

Normally these protective measures may be taken upon receiving warning of an expected attack, but in event of a surprise attack the first warning may be the nuclear explosion itself. The explosion must be detected and identified and the warning or protective devices actuated within a fraction of a second to give such devices a chance to operate. The short warning time available necessitates a system which is not dependent on human actuation.

This invention relates to a system whereby a nuclear blast in the vicinity of the system is automatically detected and identified, and whereby protective measures are automatically initiated and carried out. In broad terms, the system of this invention will very rapidly provide an electrical signal upon detection of a nuclear detonation, which signal may be utilized to take desired protective measures, including closing blast valves, energizing or shutting down utility circuits, sounding warnings, and other operations.

It is characteristic of all known types of nuclear explosions that the explosion is accompanied by a so-called optical or thermal signal in the form of released ultraviolet, visual, and infrared energy which is concentrated primarily in two pulses. The relative amplitude and duration of the two light flashes from the nuclear blast vary widely with the size and type of the nuclear device, atmospheric conditions, and other factors, but the two-pulse wave form is characteristic of the thermal signal which occurs in any nuclear blast.

The pattern of the released thermal energy of nuclear detonations is further characterized by a peculiar and unique difference in the shape of the two pulses. The first or initial pulse occurs simultaneously with detonation of the weapon, and is typically a very fast rising, sharp spike of short duration, usually of roughly about 7–15 milliseconds duration. The energy of this first pulse is primarily in the ultra-violet spectrum, although infrared energy is also preesnt to a lesser extent. The second pulse follows the first by a time lag which varies with the size of the weapon, and which may be from a few hundred milliseconds to several seconds. Typically, the second pulse is much "broader" and slower rising than the first, and has a duration of at least above a second; usually approximately 99% of the total thermal energy of the explosion is released during this second pulse. Its energy is primarily in the visual and infrared spectrums. The total duration of both pulses may be several seconds. Between the fast rising spike-like first pulse and the slow rising, longer lasting second pulse, released thermal energy is relatively low, so that the pulses are quite distinctly separated. The pressure or shock wave of the blast follows the second pulse, and may arrive very rapidly thereafter, depending on the nearness and size of the blast. No other type of event, either natural, such as lightning, or man-caused, is known to emit thermal energy in such a pattern.

Detection systems based solely upon recognition of a fast rising spike of thermal energy have proven unreliable and subject to false alarms, because similar light energy pulses are sometimes produced by lightning, chemical explosions, and other non-nuclear events. For this reason, systems based upon detection of a fast rising energy pulse alone have been undesirably indiscriminate in operation. Apart from their psychological effect, false alarms have sometimes required manual resetting of blast valves, which may be time consuming where there are several valves hundreds of feet apart, especially if explosive cartridges must be replaced.

For this reason, most nuclear blast detection and alarm systems are based upon recognition of a fast pulse of predetermined amplitude followed by a relatively slow rising, longer lasting thermal pulse corresponding to the second pulse of a nuclear blast. In the past, such recognition has been based upon photoelectric actuation of an electronic circuit by a fast-rising pulse of radiation, which circuit then sets up an associated second circuit for subsequent actuation by a slower rising pulse of radiation. If a slow rise pulse of predetermined intensity is detected after detection of the fast rising pulse, the protective measures are thereupon initiated.

Although past systems based upon recognition of the two-pulse characteristic of nuclear detonations have had a much lower incidence of false alarms than single pulse detection systems, the inherent necessity in past systems of sensing and responding to the slow rise second pulse has rendered them undesirably slow in operation. The protective measures, actuated following detection of the second pulse, require a certain amount of time in which to be completed; blast valves may, for example, require a tenth of a second to close, and the shock wave, if the blast is a near miss, might arrive before the valve is closed. In such systems, the time required after detection of the secondary pulse to initiate and execute the mechanical protective measures could, in some instances, cause those measures to be too late or to be ineffectual in part.

This invention is predicated upon the conception, discovery, and determination that detection of a fast-rise time thermal signal can be utilized to tentatively establish recognition of the blast and to initiate or actuate various protective or alarm measures, especially those which are time-critical such as closing shelter blast valves, and that detection thereafter of a slow rising second thermal signal can be utilized to confirm the tentative recognition established by detection of the first signal, to permit the previously initiated measures to continue and to initiate less time-critical measures such as diesel shutdown, or to return the system to normal in the event a second pulse is not received. In this manner, significant and perhaps vital extra operating time is attained.

Otherwise expressed, unlike past systems, the blast detecting and alarm system of this invention takes advantage of detection of a fast-rise time thermal pulse to achieve quicker operational response to detonation of a nuclear weapon, and incorporates reversible primary protective means which are automatically returned to normal if the tentative identification of the first pulse is not verified by detection of a slow rise time second pulse within a pre-established time thereafter.

More specifically, this system responds to a fast rising, high amplitude light or thermal pulse to execute or set in operation the primary or most critical protective measures, such as closing the blast valves in shelter air ducts. Detection of the fast pulse also initiates a time period

of predetermined duration, during which a slow rising signal must be detected to permit the previously initiated primary measures to be completed or to remain in effect if completed. A slow-rise pulse occurring during this period corroborates the initial, possibly inaccurate blast recognition established by detection of the fast spike, and permits the blast valves to continue closing, or to remain closed if they have already closed. In addition, detection of a slow rise signal may also be used to actuate less time-critical secondary protective measures, such as shutting down diesel engines, activating the filter system, closing dampers, sounding alarms, and other measures which cannot so readily be reversed or returned to normal status.

If no slow rise is detected after the fast rise signal, the system outputs are inhibited and the system is returned to normal, without serious "false alarm" effect.

Another important feature of the invention resides in the concept that if the system detects only a slow rise signal, not preceded by a fast rising signal, all of the protective measures are thereupon actuated.

The system advantageously incorporates blast valves of a type which can be remotely reopened without adverse effect, so that if the first signal is not confirmed by a second signal the valve can automatically be returned to open on normal condition. Preferably, although not necessarily, the system is used in association with one or more blast valves which are pneumatically operated, each having a movable valve member positionable in either open or closed position by a piston to which air under pressure is supplied through a solenoid controlled three-way valve. With a blast valve of this type, detection of a fast rising pulse causes the system to supply an electrical output which actuates the blast valve pneumatic control so that the blast valve is started closing. The amount of time required for closure depends upon the specific size and construction of the blast valve, but in any event, whether or not the valve is fully closed, if the initial thermal impulse is not soon confirmed by a following slow rise impulse, the pneumatic valve controls will be reversed so that the blast valve is returned to open condition. In this manner, the blast valve, which is one of the most time-critical protective devices, is closed before arrival of the shock wave. Other protective devices or measures such as alarms, auxiliary generators, air filters and so on which are not so time-critical, and which are not so easily or so freely reversed if the initial pulse is not confirmed, are shut down or actuated only upon confirmation of the first pulse by a second pulse.

The electrical circuitry for the detecting and alarm system preferably includes optical or thermal sensor means supplying an electrical output upon detecting a pulse of light or infrared energy. Advantageously a plurality of such sensors are connected in parallel, so that a pulse from any one will cause the system to respond. The sensor responds both to fast rise pulses and to slow rise pulses by supplying an electrical output signal of related waveform; discrimination between these electrical signals is provided by a filter circuit to which the sensor or sensors are coupled.

The filter rejects very high frequency signals, and also prevents unwanted very slow rise signals from passing on. The fast rise signal is used to open a "fast output" relay which controls the primary protective measures which are to be operated upon detection of the fast signal. At the same time, a signal is provided to a circuit which controls the length of time that the fast output relay will remain open; this period can be adjusted within a time range, and after this period, if a slow rise signal has not been received, the fast output relay will be reclosed and the previously started protective measures will be cancelled, further outputs inhibited, and the system returned to normal.

A slow output relay is operated by circuitry which responds only to detection of a slow rise signal. If such a signal arrives subsequent to a fast signal and within the timed period established by detection of the fast signal, the fast output relay remains open, and the slow output relay is also opened, which may be used to start less time-critical protective measures, as previously explained.

The nuclear blast detector and alarm system which we have invented, and the concepts upon which it is based, may best be further explained by reference to the accompanying drawings in which:

FIGURE 1 is a graph which illustrates, in diagrammatic form, the general shape of the thermal energy wave produced by detonation of a nuclear device;

FIGURE 2 is a diagrammatic illustration showing a typical installation of the system we have invented, and which illustrates the general details of a suitable blast valve controlled by the system; and

FIGURE 3 is a circuit diagram of a suitable electric circuit for use in the system of this invention.

The illustration in FIGURE 1 of the approximate wave form of the thermal energy released by a nuclear detonation is intended to be representative rather than definitive. In general, as shown in the graph, the initial spike is very fast rising, and reaches its peak amplitude in about 10 milliseconds. The system of this invention responds to detection of a fast rising initial pulse having an amplitude in excess of a predetermined amount to trigger or start the blast valve closing.

It will also be seen in FIGURE 1 that the second pulse of a blast rises to its peak amplitude more gradually than the first pulse, and is longer lasting. As illustrated, the slow pulse may peak about 0.2 second (200 milliseconds) after detonation blast, although this time will vary with the size and condition of the blast.

Closure of a blast valve of the type shown in FIGURE 2 may require only 100 milliseconds, so that if, in accordance with the invention, the valve is started closing upon detection of the fast pulse, it will be fully closed by the second pulse and shock wave arrival.

In FIGURE 2, the sensor whereby the thermal energy released by the blast is converted to electrical signals to actuate the system, is illustrated diagrammatically at 1. Sensors of suitable type are themselves known, and do not of themselves comprise the invention. The sensor may be positioned on a building or tower, away from the remainder of the circuitry. The electrical impulses generated by the sensor in response to an impinging thermal wave actuate a detection and logic circuit which is electrically connected to the sensor and which is shown schematically in FIGURE 2. The detection and logic circuit operates one or more electrically controlled blast valves, of which a suitable configuration is designated generally by 2.

The blast valve 2 is usually placed at the entrance to, or in, a shelter air duct, either in the air intake or exhaust or both. The valve 2 advantageously comprises a dome-shaped movable valve member 3, which is positionable with respect to a cylindrical fixed valve member 4, which in turn leads to the air duct. A cylinder 5 is supported in the center of the cylindrical member 4, and this cylinder 5 includes a movable piston 6, which is connected for moving the movable valve member 3 by a rod 7. Actuation of the piston 6 may suitably be effected through a solenoid controlled, spring return three-way valve which is designated by numeral 10 in FIGURE 2. A pump or accumulator 11 supplies air under pressure; the valve 10 has a shiftable valve member, which when its operating solenoid 12 is energized, supplies air under pressure through a line 14 to chamber 13 beneath the lower end of the valve piston 6. Air under pressure is supplied at all times to chamber 15, above piston 6. Equal pressures in chambers 13 and 15 establish a differential force on piston 6 by reason of the displacement of rod 7. This differential force causes the piston 6, rod 7, and the movable valve member 3 to open and remain in open position. When the solenoid 12 is de-energized, a spring 19

moves the shiftable valve member of the control valve 10 so that the pressurized air supply to chamber 13 is blocked and pressure in chamber 13 is released to atmosphere at port 16. At the same time, pressure from pump 11 is maintained in chamber 15, causing piston 6 to move downwardly and close the blast valve, effecting a tight seal between the movable head 3 and the body 4. Thus, so long as solenoid 12 is energized, the blast valve remains open, and when the solenoid 12 is de-energized, the valve will automatically close. It will be seen that the system is fail safe, in that if for any reason electrical energy is disrupted the blast valve will close.

By reason of the partial actuation of the system in response to fast rising signals, it is contemplated that the blast valve 2 may be closed from time to time in response to spurious signals such as lightning, shell burst, and so on. Such false alarms do not here present a problem, inasmuch as the valve will soon automatically be reopened, and also because the other, less time-critical measures do not operate until the entire blast waveform has been detected and recognized.

FIGURE 3 is a schematic diagram of one embodiment of a suitable electronic circuit for operating the detecting system of this invention. It will be realized that the operating principles of the system we have invented may be embodied in other electronic circuits, and that the circuit illustrated in FIGURE 3 is given by way of completeness of disclosure rather than by way of limitation.

In FIGURE 3, the values of the various circuit resistors and capacitors are indicated beside the respective circuit elements. It is understood that the figures beside the resistors refer to ohms, while the figures beside the capacitors refer to microfarads.

The circuit illustrated in FIGURE 3 operates a pair of output relays, one of which is a fast signal relay designated by A, and the second of which is a slow signal relay designated by B. The circuit is fail-safe; that is, both relays A and B are normally energized, and actuate the various devices which they control when they are de-energized.

A power supply is connected through the normally closed contact of slow signal relay B to the protective devices which are to be actuated only upon detection of the slow signal; as previously explained, such devices may comprise alarms, air filter activating mechanisms, diesel engine controls, auxiliary utility circuits and the like. It is contemplated that relay B may have multiple contacts for actuating the various measures, or that relay B may open one or more circuits to relays which directly control the protective measures.

The power supply is also connected through the normally closed pole of slow relay B to the primary or most time-critical protective devices, for example the blast valve, through the normally closed pole of fast signal relay A. Thus, it will be seen that if relay A is de-energized, the armature of relay A will open its normally opened contact, thereby activating the blast valve. Current is maintained in relay B after relay A has opened until a slow rise pulse is detected, whereupon relay B is opened, thereby activating the secondary protective measures. It will also be apparent that opening of relay B, even though relay A may be closed, will activate all of the protective measures, both the blast valve and the secondary measures, because the contacts of relay A are in series with the contacts of relay B.

In FIGURE 3, each of the various functional groups or components of the circuit is shown within dotted lines. Broadly speaking, the circuit comprises a sensor, an amplifier, a filter, a fast trigger logic section, fast output circuitry, a slow trigger logic section and slow output circuitry.

The sensor may be a simple infrared detector. The phototube, which is identified as V_1 in FIGURE 3 is a type 928 tube. This tube changes the light energy of the pulse directly into an electrical wave the envelope of which approximates that of the received light. The electrical signal is developed across resistor R_1 and is directly coupled to the grid of tube V_2, which may be a 12AU7 tube. Tube V_2 is a cathode follower used to transform the high impedance of resistor R_1 to a low impedance suitable for coupling through a long cable. Resistor R_2 and capacitor C_1 filter out any ripple present on the +100 volts input to the sensor. Resistor R_3 acts as a sensitivity control for the phototube V_1. It has been determined in actual practice that by this control the system may be set so as to be responsive to only the closest lightning flashes. It is contemplated that the sensor may be heated by suitable means not shown, for all-weather operation at a position removed from the remainder of the electronic components. Except for extreme cases, the sensor is unresponsive to lightning, the radiant energy of which is primarily in the ultraviolet spectrum.

Basically, the signal amplifier is a feed-back pair of amplifier stages employing complementary transistors achieving a minimum gain of 10. The two amplifier stages are similar, the only difference between them being capacitor C_2 in the second stage, which is an oscillation suppressing capacitor, and capacitor C_3 also in the second stage, which is a coupling capacitor for the filter section. The amplifier includes transistors T_1, T_2, T_3, and T_4; T_1 and T_3 are type 2N1302, and T_2 and T_4 are type 2N1303 transistors. A resistor R_4 and a diode D_1 set the bias for transistor T_1. Similarly, a resistor R_5 and a diode D_2 set the bias for transistor T_2. Resistors R_6 and R_7 allow sufficient current to flow through transistors T_1 and T_2 respectively to offset changes due to I_{co}. The Zener diode Z_1, diode D_3 and resistor R_8 limit the emitter to collector voltage on transistor T_1. In the second stage, Zener diode Z_2 and resistor R_9 have a similar effect. Diode D_3 also prevents excessive positive signals from damaging transistor T_1.

Resistors R_{10} and R_{11} form the collector load for transistor T_2 and also the feed-back resistors. In the second stage, resistors R_{12} and R_{13} have a similar function.

Gain adjustment is accomplished by a potentiometer R_{14} connected as a rheostat between amplifier stages.

The filter is basically a low-pass filter consisting of two L sections, comprised respectively by resistor R_{20} and capacitor C_{10}, and resistor R_{21} and capacitor C_{11}. Frequencies above 700 cycles per second are not passed through the filter. Capacitor C_{12} prevents very slow rise-time signals, such as changes in ambient sunlight, from passing through to the fast trigger logic section.

The fast trigger logic section is composed of a Schmitt trigger and a wave-forming network. Transistor T_5 is normally on, controlled by resistors R_{22} and R_{23}. Capacitor C_{13} bypasses R_{22} to speed up the switching time of the circuit. Diode D_4 prevents large negative signals from damaging transistor T_6. Both transistors T_5 and T_6 may suitably be type 2N1302 transistors.

Capacitor C_{14} and resistor R_{24} form a differentiating network to change the flattop pulse of the Schmitt trigger to a positive and then negative spike.

The fast output circuitry includes a flip-flop or bistable multivibrator which directly controls the fast signal relay A. The flip-flop is formed by transistors T_7 and T_8, which may both be type 2N1302 transistors. Capacitor C_{16} isolates the fast output circuitry from external D.C. circuits. If the anode side of diode D_6 is raised in the positive direction, the base of transistor T_7 will also be raised positive.

The collector load of transistor T_8 is made up of resistor R_{30} and the winding of relay A. Resistor R_{30} limits the voltage across relay A to prevent over-voltage damage.

A unijunction transistor T_9, which may be a type 2N491 transistor, forms an automatic reset for the flip-flop made up of transistors T_7 and T_8. Resistors R_{31} and R_{32} and capacitor C_{18} form an adjustable time constant in the emitter of transistor T_9. When the collector of

transistor of T_8 moves toward the supply voltage, due to the positive signal at the base of transistor T_9, the voltage across capacitor C_{18} and the emitter of transistor T_9 start moving toward the supply voltage also. However, the rate of voltage rise is limited by R_{31} and R_{32}. When the emitter voltage reaches approximately 60% of the voltage on base 2 of the transistor T_9, the transistor will conduct, developing a positive spike across resistor R_{33}. Upon conduction of transistor T_9, the charge is removed from capacitor C_{18}. This spike is coupled through diode D_7 to the base of transistor T_8 causing the flip-flop to return to its normal state.

Resistor R_{30} of the fast output circuitry is connected to an AND gate of the slow trigger logic section. The signal from the filter is also coupled to the AND gate of the slow trigger logic section. This section includes an AND gate, an integrating circuit, a coupling transistor, and a Schmitt trigger. Zener diode Z_4 is used to reduce the signals coming through diode D_{10} (about 16 volts) to approximate the signals coming through D_{11} (4 to 10 volts). Diodes D_{11} and D_{12} and resistor R_{35} form an AND gate. Diode D_{13} shorts large negative signals to ground. Resistor R_{36} and capacitor C_{20} form a 150 millisecond time constant integrating circuit. The base voltage of transistor T_{10}, which, like transistors T_{11} and T_{12} may suitably be a type 2N1302 transistor, is normally low because of current flow through R_{36}, D_{12}, and R_{37}. When both D_{12} and D_{11} are prevented from conducting by application of positive voltage at their cathodes, capacitor C_{20} will change toward the supply voltage. This exponentially changing voltage is coupled through transistor T_{10}. The time constant determined by R_{36} and C_{20} is such that the voltage on C_{20} will not reach a value sufficient to trigger the following Schmitt trigger for approximately 50 milliseconds.

The remainder of the slow trigger logic circuitry is very similar to the fast trigger logic. The resistance of resistor R_{40} is 10K ohms. as opposed to 22K ohms resistance of the corresponding resistor in the fast trigger logic section, in order to be compatible with transistor T_{10}. A diode corresponding to D_5 of the fast trigger logic section is not needed in the slow trigger logic section as diode D_{13} in the slow trigger logic section performs the same function.

The slow output circuitry is similar to the fast output circuitry previously described. Transistors T_{13} and T_{14} form a flip-flop; both transistors may be type 2N1302 transistors. The circuit of transistor T_{13} is identical to the circuit of corresponding transistor T_7 in the fast output circuitry. The circuit of transistor T_{14} is identical to that of transistor T_8 of the fast output circuitry. The circuit of transistor T_{15} which is a type 2N491 transistor, is similar to that of transistor T_9 in the fast output circuitry, the only difference being that the time constant, which in the slow output circuitry is determined by R_{41} and C_{21}, is fixed, taking approximately one-half second to reach sufficient voltage to allow transistor T_{15} to conduct.

Diodes D_{15} and D_{16} are in parallel with the relay coils of the fast and slow signal relays A and B respectively and suppress the voltage spike produced by sudden removal of coil voltage.

When the circuit shown in FIGURE 3 detects a thermal signal, the infrared energy of the signal is transformed into an electrical signal by the phototube and then sent on to the amplifier by the cathode follower in the sensor. The sensor output signal is a voltage of positive sense. The signal is amplified by the amplifier and coupled to the filter section. As previously explained, the filter rejects very high frequency signals and also prevents unwanted very slow rise-time signals from passing on to the fast trigger logic. The output of the filter section is coupled to the fast trigger logic and to the slow trigger logic.

A fast or slow signal of approximately 4 volts amplitude will cause the Schmitt trigger circuit in the fast trigger logic section to provide a positive pulse which is coupled to the flip-flop in the fast output circuitry, which directly controls the fast signal relay A. The pulse from the Schmitt trigger in the fast trigger logic causes the flip-flop in the fast output circuitry to change state, opening relay A; at the same time, a signal is provided to the slow trigger logic and to the unijunction transistor circuit in the fast output circuitry which controls the length of time the fast output relay will remain open. This time can be adjusted from one to three seconds, and after this time, the flip-flop in the fast output circuitry will automatically be reset and the fast signal relay A will again close.

The signal from the filter is also coupled to the AND gate in the slow trigger logic. This gate is also fed by the output from the fast output circuitry. The signal from the filter will pass through the AND gate only when the output from the fast output circuitry is also present, indicating that the signal has been preceded by a fast spike. The signal from the amplifier must be greater than approximately 50 milliseconds in duration, before the integrating will allow sufficient amplitude to be reached to cause the Schmitt trigger of the slow trigger logic to change state. Thus, the fast signal will not operate the slow trigger logic. However, if a slow rise-time signal arrives within the time set by the fast output circuitry, the slow rise-time signal will pass through the integrating circuitry in the slow trigger logic and trigger the Schmitt trigger. The output of the slow trigger logic is a positive pulse which is coupled to the slow output circuitry. The length of time the slow signal relay B remains open is not adjustable, but is preset at approximately 0.5 second. Thus, the arrival of a fast pulse only will cause the fast signal relay A to open and then close without causing the slow signal relay B to be opened. On the other hand, if a slow signal only is received, the fast signal relay will still be opened, thereby allowing the signal to pass on to the slow trigger logic and ultimately opening the slow signal relay.

It is contemplated that the contacts of relay A may be connected in series with the solenoid control of the blast valve. It is also contemplated that relay B may have multiple contacts, each connected in an appropriate operating circuit for controlling the various secondary protective measures which are to be controlled by relay B.

From the foregoing, it will be seen that we have invented a nuclear blast detector and alarm system which responds to the detection of a fast rise-time thermal signal to initiate the more time critical protective measures, and which uses a subsequent slow-rise thermal signal to confirm the previously initiated protective measures as correct, thereby avoiding the time lag which has been present in prior blast detection systems.

Having described our invention, what is claimed is:

1. In a nuclear explosion protection system including a primary blast protective device and at least one secondary protective device, the operation of said primary device being time critical on occurrence of a nuclear explosion, said secondary device being substantially less time critical in operation than said primary device but being less freely reversible in operation once actuated, both said primary and secondary devices being electrically controlled,

apparatus for operating said primary and secohdary devices in response to a nuclear explosion comprising,

a sensor responsive to radiant energy to produce an electrical output corresponding in form and amplitude to said radiant energy,

and electrical circuit means for separately actuating said primary device and said secondary device,

said circuit means being electrically connected to said sensor and being responsive to the output from said sensor of an electrical signal corresponding to the

initial radiant energy pulse of a nuclear explosion to thereupon operate said primary device but not said secondary device,

said circuit means being responsive to the output from said sensor corresponding to the second radiant energy pulse of a nuclear explosion to thereupon actuate said secondary device,

said circuit means including means for returning said primary device to its original status if an electrical signal corresponding to the second pulse of a nuclear explosion is not supplied by said sensor within a pre-established time interval following a signal from said sensor corresponding to the first pulse of a nuclear explosion.

2. In association with a blast shelter, the system comprising,

a reversible, fluid pressure operated blast valve,

electrically operated control valve means for applying said fluid pressure to open and close said blast valve,

a thermal radiation sensor supplying an electrical signal corresponding to thermal radiation impinging on it,

and electrical circuit means for actuating said control valve means to cause said blast valve to open and close,

said circuit means being electrically connected to said sensor and being responsive to the output by said sensor of an electrical signal corresponding to the initial thermal pulse of a nuclear explosion to thereupon actuate said control valve means to close said blast valve,

said circuit means including means for actuating said control valve means to reverse the closure of said blast valve if an electrical signal corresponding to the second thermal pulse of a nuclear explosion is not supplied by said sensor within a pre-established time interval following a signal from said sensor corresponding to the first thermal pulse of a nuclear explosion,

said circuit means being responsive to an electrical signal from said sensor corresponding to the second thermal pulse of a nuclear explosion to actuate said control valve means to close said blast valve if said blast valve has not previously been closed.

3. The system comprising,

an electrically controlled reversibly operable blast valve,

electrically operated secondary devices, said secondary devices being less time critical in operation than the blast valve,

a sensor responsive to thermal radiation impinging thereon to produce an electrical signal corresponding to the thermal radiation,

and electrical circuit means for actuating said blast valve and said secondary devices,

said circuit means being electrically connected to said sensor and being responsive to a signal from said sensor corresponding to the initial thermal pulse of a nuclear explosion, to thereupon initiate the closure of said blast valve but not to actuate said secondary devices,

said circuit means being responsive to an electrical signal from said sensor corresponding to the second thermal pulse of a nuclear explosion to thereupon actuate said second devices and simultaneously to initiate the closure of said blast valve if said blast valve was not previously closed,

said circuit means including means for causing said blast valve to be reopened in the event that an electrical signal corresponding to the second thermal pulse of a nuclear explosion is not supplied by said sensor within a pre-established interval, not exceeding a few seconds' duration, beginning with a signal from said sensor corresponding to the first thermal pulse of a nuclear explosion.

4. The system comprising,

an electrically controlled blast valve,

electrically controlled secondary blast protective devices, said secondary devices being less time critical in operation than the blast valve,

a sensor responsive to radiation impinging thereon to deliver an electrical signal corresponding to the radiation,

and electric circuit means for separately actuating said blast valve and said secondary protective devices,

said circuit means being electrically connected to said sensor and being responsive to the output by said sensor of an electrical signal corresponding to the initial pulse of a nuclear explosion, to thereupon close said blast valve,

said circuit means being responsive to an electrical signal from said sensor corresponding to the second pulse of a nuclear explosion to thereupon actuate said secondary protective devices,

said circuit means including electric means causing said blast valve to reopen in the event that an electrical signal corresponding to the second pulse of a nuclear explosion is not delivered by said sensor within a pre-established time interval following a signal from said sensor corresponding to the first pulse of a nuclear explosion.

5. A nuclear blast protective system including,

a reversibly operable blast valve,

electrically controlled means for reversibly operating said blast valve,

electrically controlled secondary protective devices less time critical in operation than said blast valve, said secondary blast protective devices including air filters and auxiliary utilities,

a thermal radiation responsive sensor for converting thermal radiation detected by said sensor to a corresponding electrical signal,

circuit means for separately operating said blast valve and said secondary protective devices, said circuit means being actuated by signals from said sensor,

said circuit means including, a fast trigger circuit closing said blast valve in response to a signal from said sensor corresponding to the fast rise-time thermal pulse of a nuclear blast,

a slow trigger circuit closing said blast valve and actuating said secondary protective devices in response to a signal from said sensor corresponding to the slow rise-time thermal pulse of a nuclear blast,

and electric means causing said blast valve to be reopened if a signal from said sensor corresponding to the slow rise-time pulse of a nuclear blast is not received within a fixed time interval of at most a few seconds duration following a signal corresponding to the fast rise-time pulse of a nuclear blast.

6. A nuclear blast protective system including,

an air pressure operated blast valve,

an electrically operated control valve for opening and closing said blast valve,

electrically controlled secondary protective devices less time critical in operation than said blast valve,

thermal radiation responsive sensor means for converting detected thermal radiation to corresponding electrical signals,

circuit means for separately operating said control valve and said secondary protective devices, said circuit means being actuated by signals from said sensor means,

said circuit means including,

filter means for separating the fast electrical signal produced by said sensor means upon detection thereby of the fast rise-time initial thermal pulse of a nuclear blast from the slow signal produced by said sensor

means upon detection thereby of the slow rise-time second thermal pulse of a nuclear blast,

a fast trigger circuit responsive to said fast signal for closing said blast valve in response thereto,

a slow trigger circuit responsive to either said fast signal or said slow signal for actuating said secondary protective devices in response thereto and simultaneously closing said blast valve if said blast valve was not previously closed by a fast signal,

and fast signal actuated timing means reopening said blast valve if a slow signal is not received within a fixed time interval of at most a few seconds duration following a fast signal.

7. Apparatus comprising,

a reversible blast valve capable of closing in less than about 200 milliseconds,

electrically controlled pressure means operable upon actuation to selectively close and open said blast valve,

and means sequentially responsive to the fast rise-time initial radiant energy pulse of a nuclear blast and to the slow rise-time second radiant energy pulse of a nuclear blast, said last named means being responsive to said initial pulse to actuate said electrically controlled pressure means to thereupon close said blast valve and to actuate said pressure means to reopen said blast valve at the end of a period of 2–10 seconds following said initial pulse if said second pulse does not occur within said period, said last named means being responsive to said second pulse to permit said blast valve to remain closed if said second pulse does occur within said period.

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RALPH. G. NILSON, *Primary Examiner.*

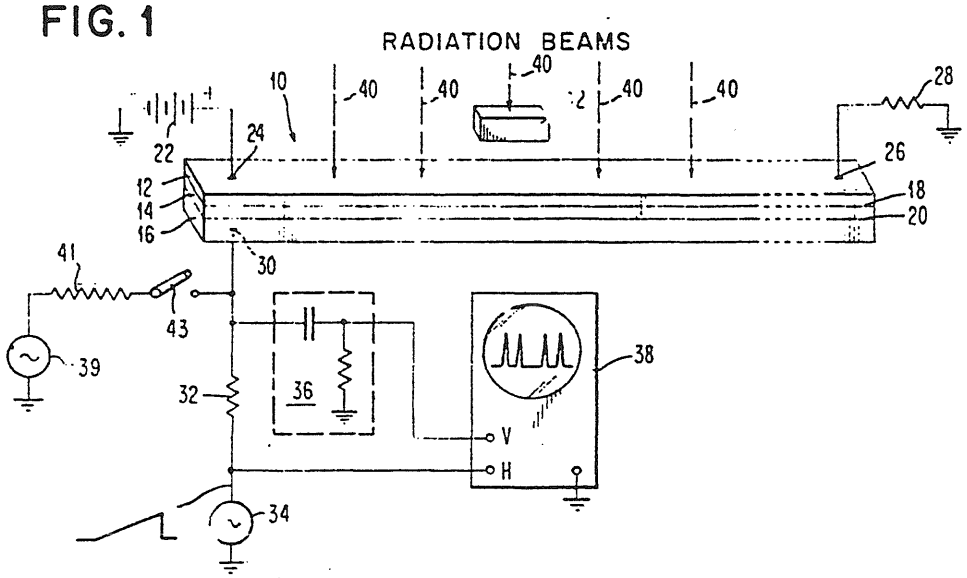
ARCHIE R. BORCHELT, *Examiner.*

May 2, 1967 J. W. HORTON ETAL 3,317,733

RADIATION SCANNER EMPLOYING RECTIFYING DEVICES AND PHOTOCONDUCTORS

Filed May 10, 1963 3 Sheets-Sheet 1

FIG. 1



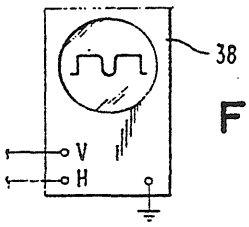


FIG. 2

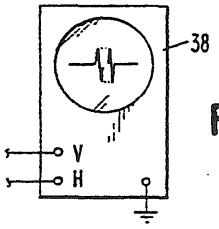


FIG. 2a

FIG. 3

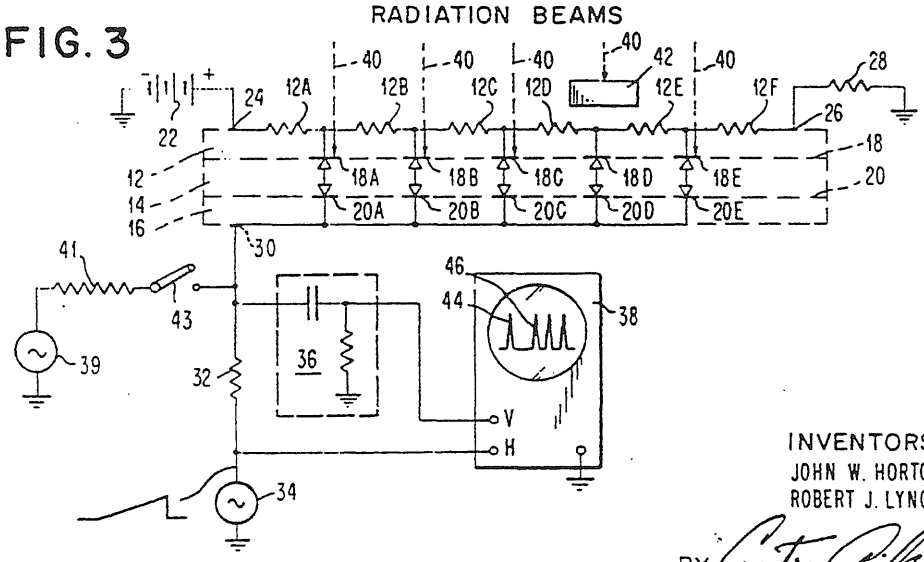


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FIG. 4

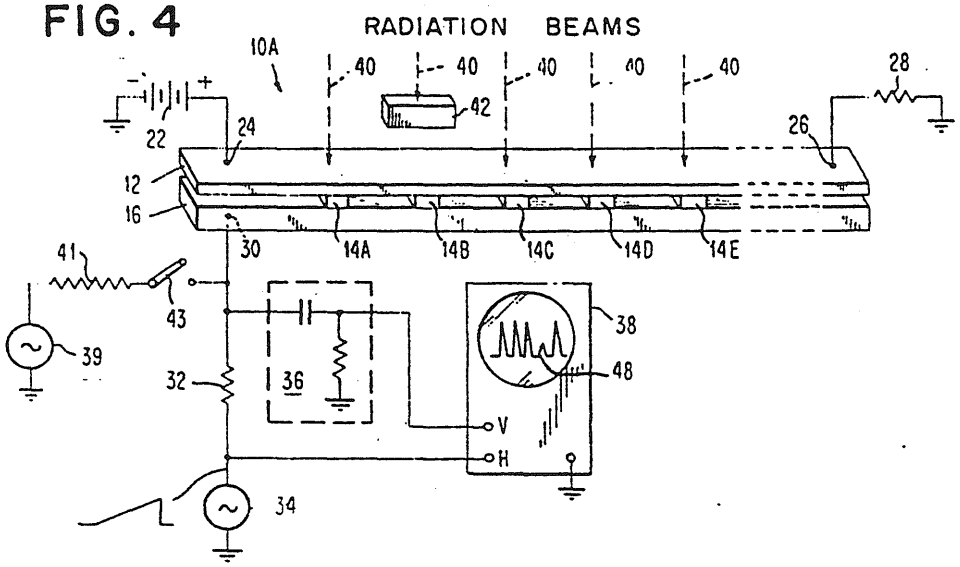


FIG. 5

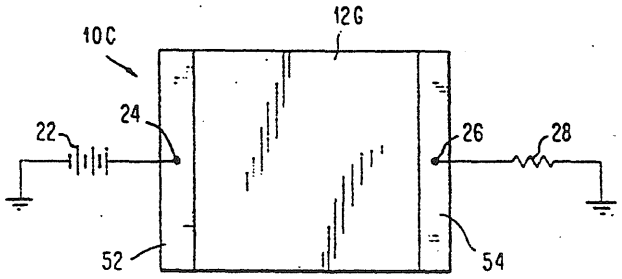


FIG. 6

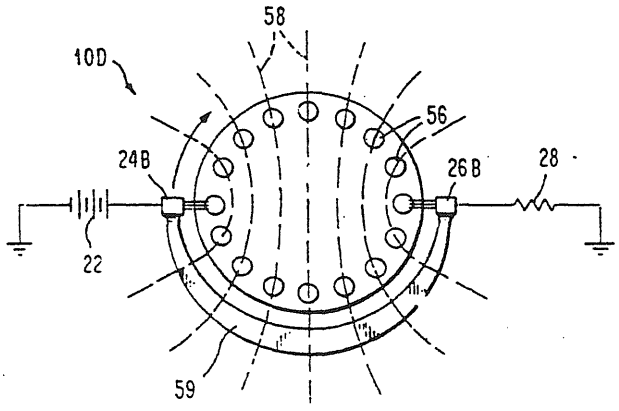


FIG. 7

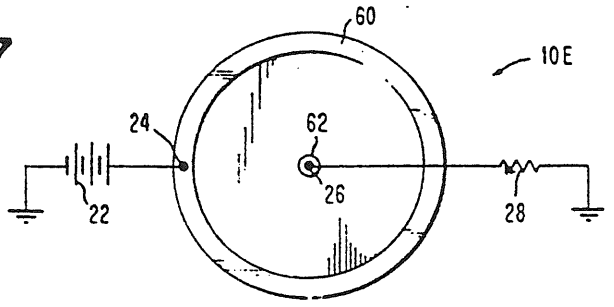
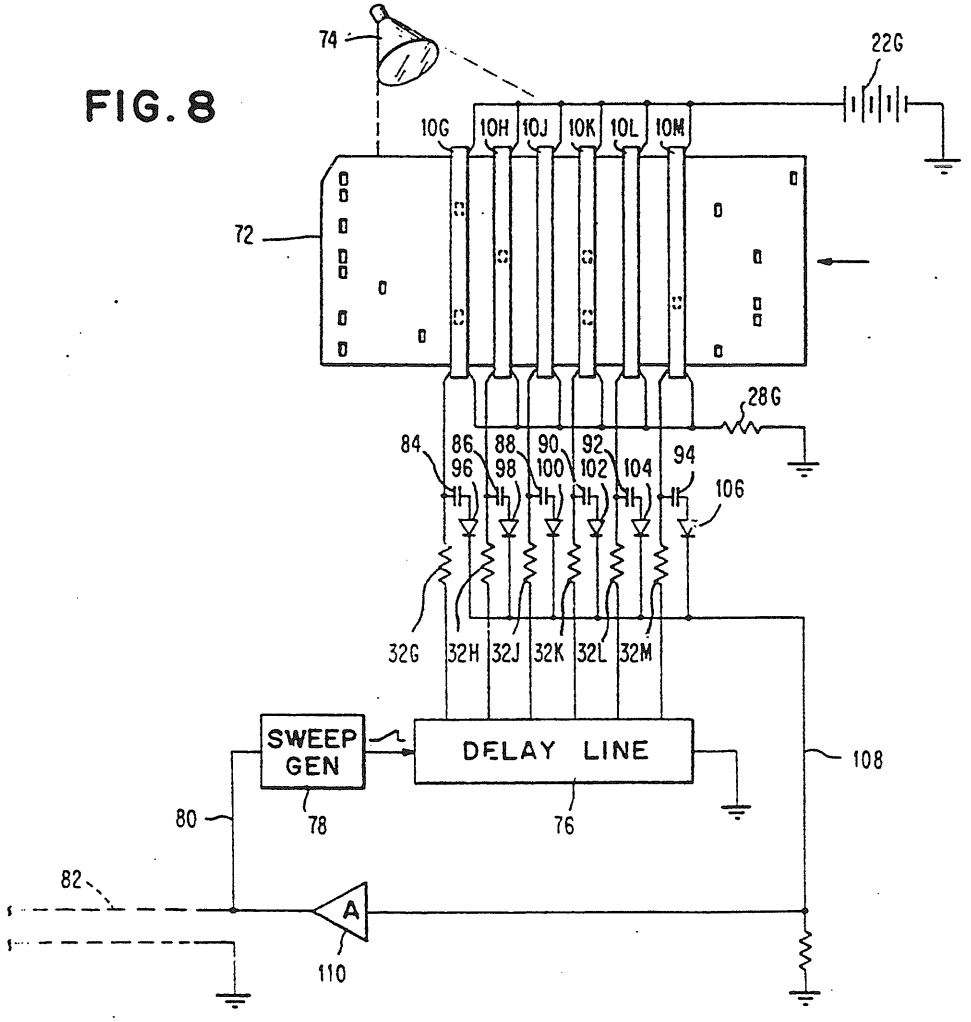

60
10E
24
62
26
22
28

FIG. 8


74
22G
10G
10H
10J
10K
10L
10M
72
28G
84
86
96
88
98
90
100
92
102
104
94
106
32G
32H
32J
32K
32L
32M
SWEEP GEN
DELAY LINE
108
80
78
76
82
A
110

United States Patent Office

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RADIATION SCANNER EMPLOYING RECTIFYING DEVICES AND PHOTOCONDUCTORS

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20 Claims. (Cl. 250—211)

This invention relates to scanners of patterns of radiant energy and more particularly to electrical solid-state systems and devices which are capable of deriving electrical signal patterns from radiant signal patterns appearing along a line or in an area.

There are many presently known radiation scanners including optical image scanners such as cathode ray flying spot scanners, orthicon and vidicon tubes, and so forth. All of these commonly used scanning systems are generally quite complicated and expensive. They are often large and awkward in size, employing high voltages, and are delicate and easily subject to damage, and have limited useful lives.

Acordingly, it is one object of the present invention to provide radiation scanners which are simple, compact, and inexpensive.

It is another object of the present invention to provide radiation scanners which operate without the use of high voltages.

It is another object of the present invention to provide radiation scanners which are rugged and long lived.

Another object of the invention is to provide radiation scanners of the above description which are capable of high speed operation.

Other objects and advantages of this invention will be apparent from the following specification and the accompanying drawings which are as follows:

FIG. 1 is a schematic circuit diagram illustrating one embodiment of the present invention.

FIG. 2 is a schematic representation of a cathode ray oscilloscope showing a variation in electrical output available from the system of FIG. 1.

FIG. 2*a* is a view similar to FIG. 2 showing another variation in electrical output available from the system of FIG. 1.

FIG. 3 is a schematic circuit diagram illustrating the principle of operation of the embodiment of FIG. 1.

FIG. 4 is a schematic circuit diagram illustrating a modified embodiment of the invention.

FIGS. 5, 6 and 7 are partial schematic views illustrating several modifications of the embodiment of FIG. 1 which are adapted for scanning areas.

And FIG. 8 is a schematic diagram of another area scanning modification of the invention.

In carrying out the above objects of the invention in one preferred embodiment thereof, a radiation scanner is provided including an elongated multiple layer structure having an intermediate layer and two outer layers substantially defining the entire upper and lower surfaces of the elongated structure. The intermediate layer is joined to both outer layers throughout substantially the entire length thereof and the materials of the layers are selected to form an elongated asymmetrically conductive semi-conductor junction at each of the joints, the junctions having oppositely poled asymmetry. At least one of the junctions has conductive properties responsive to radiation received thereby, and at least one of the outer layers has electrical connections at laterally spaced positions thereon and arranged for connection to sources of different bias voltage levels. The other outer layer has at least one electrical connection arranged to be connected to a source of another bias voltage level. A source

of a sweep voltage difference is applied between the outer layers, and a detector is connected in circuit between the outer layers for detecting functions of the current between the outer layers.

Referring more particularly to FIG. 1 there is shown an elongated multiple layer structure **10** including an upper layer **12**, an intermediate layer **14** (which is also sometimes referred to as a central layer), and a lower layer **16**. Upper and lower layers **12** and **16** are sometimes referred to hereinafter as outer layers as they define the upper and lower surfaces of the structure **10**. The outer layers **12** and **16** are each joined to the central layer **14** at joints **18** and **20**, and the materials of the layer are chosen so that joints **18** and **20** form oppositely poled asymmetrically conductive semi-conductor junctions or contacts. One of the junctions, such as **18**, has conductive properties responsive to radiation such as photoconductivity. The upper layer **12** also serves as a resistive voltage divider, having a source of bias voltage schematically indicated by battery **22** connected to the upper layer as indicated schematically at **24**, and having a connection, as schematically indicated at **26**, through a resistor **28** to ground. The lower layer **16** is connected at **30** through a resistor **32** to a source **34** of ramp or sweep voltage. Transient changes in the voltages across resistor **32** corresponding to a frequency higher than the ramp voltage frequency are detected by means of a filter network **36** through which the transient voltage signals are supplied to a cathode ray oscilloscope **38**. The upper surface of the structure **10** is exposed to a number of discrete beams of light, as indicated by the arrows **40**, and one of the beams is obstructed by an opaque object, such as indicated at **42**. As a result, a trace, such as indicated on the face of the cathode ray oscilloscope **38**, is obtained which is indicative of the pattern of light striking the upper surface of structure **10**. An auxiliary alternating current source indicated at **39** having a high impedance as schematically illustrated by resistor **41** is arranged for connection to point **30** by means of a switch **43**. Source **39** provides an alternative mode of operation described in detail below in connection with FIG. 2*a*.

FIG. 2 is a partial view showing only the cathode ray oscilloscope **38**, and illustrating the trace which is obtained with the system of FIG. 1 when the structure **10** is uniformly illuminated except for the obstruction **42**. It is to be seen from FIG. 2 that the presence of the obstruction **42** is clearly indicated with uniform illumination. With the discrete beams of light as illustrated in FIG. 1, the cathode ray tube trace shows a positive blip for each unobstructed beam of light, with no blip being present for the obstructed beam. However, with continuous illumination, the trace pattern clearly shows the boundaries of the obstruction.

FIG. 3 schematically illustrates the principle of operation of the embodiment of FIG. 1. This figure corresponds to FIG. 1 except that schematic circuit components are illustrated for the structure **10** which indicate the electrical functions performed by the different portions of the structure **10**. Thus, the fact that the upper layer **12** serves as a voltage divider resistance is schematically illustrated by the presence of the resistors **12A** to **12F**. Furthermore, the operation of the junctions **18** and **20** as oppositely poled asymmetrically conductive semi-conductor junctions is schematically illustrated by the diode circuit symbols at **18A** through **18E** and **20A** through **20E**. These devices, such as **18A** and **20A**, are connected back to back in individual pairs. Thus, for purposes of the present analysis, it may be considered that the semiconductor junction **18** is divided into a series of discrete junctions **18A** through **18E**, and that the junction **20** is divided into a number of discrete junctions **20A** through

20E. These discrete junctions are considered to occur at the locations where the discrete light beams 40 impinge upon the upper surface of structure 10. Since the junction 18 displays photoconductive properties, the light beams 40, or electron-hole pairs released in layer 12 by light beams 40, must reach the junction 18. Thus, the light beams 40 in FIG. 3 are shown as penetrating to the individual junctions 18A through 18E.

The operation of the circuit, as schematically illustrated in FIG. 3, may be explained as follows: Before the commencement of the sweep voltage from generator 34, the lower layer 16, which serves essentially as a conductive bus, is effectively connected through resistor 32 and generator 34 to ground. Thus, it may be said to be biased to zero. At the same time, the voltage from source 22 is divided through the voltage divider network provided by resistors 12A through 12F and 28 to provide a series of elevated voltage values at the diode junctions 18A through 18E. While these voltage values decrease from left to right in the diagram, even the lowest voltage value at diode 18E is a measurable positive voltage above ground because of the drop through resistors 12F and 28. For instance, at 18E the voltage may be approximately +3 volts. Thus, all of the upper diodes 18A through 18E are back biased, while all of the lower diodes 20A through 20E are forward biased. However, since the back biased diodes 18A, 18B, 18C and 18E are illuminated, and have photoconductive properties, they are conductive in the back biased condition. All of the resultant photocurrent through the diode pairs 18A, 20A and 18B, 20B, and 18C, 20C and 18E, 20E flow through to the lower layer 16, which acts as a conductive bus, and then through resistor 32 and generator 34 to ground. As the ramp voltage from generator 34 begins, the diode pair 18E, 20E is the first to achieve a null voltage condition in which the voltage of the lower layer 16 is raised to a level equal to the voltage of the upper layer in the vicinity of the diode 18E. The photocurrent through diode 18E is thus abruptly terminated and this abrupt change in current is detected across the load resistor 32 by the network 36, and the resultant signal is thus applied to the cathode ray oscilloscope causing an upward spike in the cathode ray oscilloscope trace as indicated at 44. As the ramp voltage continues, a null voltage condition is next achieved at the diode pair 18D, 20D, but since the light beam in the vicinity of this idode pair is interrupted by the opaque object 42, there is no appreciable change in current and no spike occurs at this point in the timing of the sweep. As the sweep voltage continues to raise the potential of layer 16, the diode pair 18C, 20C next achieves the null voltage condition and as a result another spike, as indicated at 46, occurs in the cathode ray oscilloscope trace. Similarly, as the diode pairs 18B, 20B and 18A, 20A successively achieve the null condition, the resultant current changes provide additional spikes in the cathode ray oscilloscope trace. Thus, it is to be seen that the cathode ray oscilloscope trace provides a visual indication which may be remote from the device 10, which shows which of the beams 40 has been interrupted by the opaque object 42.

After the diode pair 18E, 20E achieves the null condition, as the sweep voltage progresses, the voltage condition is reversed across this pair of diodes, thus, the voltage is in a direction to back bias the diode 20E and forward bias the diode 18E. However, substantially no current flow results from this condition because the diode 20E is not illuminated, and the diode 20E thus serves essentially as a blocking diode. Similar action is obtained from the other diodes at the junction 20. This blocking action is important to the operation of this invention because, in the absence of this blocking action, the currents through the diodes which had passed the null condition would load down the sweep generator 34 so that it would be very difficult to obtain an accurate calibrated sweep operation with a minimum of power dissipation.

As the above explanation implies, the central layer 14 is intended to have a very high lateral resistance, that is, the resistance of the central layer must be high in the horizontal direction in the diagram, while having a reasonable value in the vertical direction to provide an electrical connection between the members of each of the diode pairs. Thus, while this central layer is not an insulator, its lateral or transverse resistance is intended to be so high that its conductivity is ignored for the purpose of the analysis accompanying the schematic diagram of FIG. 3. The lower layer 16 is intended to be essentially conductive, so that it will be a unipotential electrode. This conductivity may be assured by providing a metallic plated conductor connected to the lower surface by low resistance, ohmic contact.

As indicated above, the schematic circuit representation of structure 10 is idealized for the purposes of explaining the principles of operation of the invention. It will be understood that since the outer layers 12 and 16 form continuous semi-conductor junctions with the central layer 14, they actually form the equivalent of an infinite number of diode pairs spaced horizontally along the structure 10, rather than only the five that are shown. However, since those which are not illustrated do not receive optical illumination, they may be ignored for the purpose of circuit analysis. This is true because one of the diodes in each non-illuminated pair is always back biased so that the pair is essentially non-conductive if a voltage difference appears across that pair. Thus, the diode pairs only achieve significance in the analysis of the operation of FIG. 1 when the upper diode is in a position to receive illumination.

However, it has been discovered that it is not necessary to employ discrete beams of light as illustrated in FIGS. 1 and 3. It is possible to employ non-discrete illumination at the upper surface of the structure 10 and to thus obtain the advantage of the essentially infinite number of diode pairs, and to obtain an output signal as illustrated for instance by the trace shown in FIG. 2. Thus, the central depression in the trace of FIG. 2 shows the exact position of the opaque obstruction 42. Therefore, the optical resolution of this scanner, with the continuous photoconductive semi-conductor junction 18 is extremely high.

FIG. 2*a* illustrates the system output available with an entirely different mode of operation which is obtained when the high impedance alternating current generator 39 is connected into the circuit by means of switch 43. This generator is preferably a radio frequency source, operating for instance at a frequency of about 200 kilocycles. This frequency is well above the threshold of the high pass filter network 36 so that the signal is readily available to the detection apparatus including oscilloscope 38. However, whenever an illuminated portion of structure 10 is being scanned, apparently there is effectively a low impedance path for the radio frequency from generator 39 through the illuminated diode pair and through the voltage divider formed by the upper layer 12 and thus to ground either through resistor 28 or through the D.C. bias source 22. Because of this low impedance connection, most of the radio frequency voltage appears across resistor 41 and very little appears across load resistor 32 to be detected by network 36 and oscilloscope 38. However, for those locations where illumination is shielded from the scanner, such as by obstruction 42, the low impedance condition does not exist, and thus a strong signal is available from generator 39 to the oscilloscope 38. Whether or not this theory that the operation of the system with radio frequency generator 39 is correct, it has been discovered that excellent, high amplitude output signals are obtained which are essentially the inverse of the output signals obtained when the system is operated in the manner described previously. That is, a large output signal amplitude is available on the oscilloscope for darkened portions of the scanner structure 10, and by contrast virtually no output is obtained for the illuminated por-

tions. Actually, the radio frequency output signal illustrated in FIG. 2*a* results from the super-position of the radio frequency signal upon the signal which is essentially a direct current signal as illustrated by the trace shown in FIG. 2. However, the radio frequency output amplitude is so much greater than the D.C. signal amplitude that the amplifier of the oscilloscope **38** is turned down so that the D.C. component of the output signal is reduced almost to the vanishing point. Thus, the trace shown in FIG. 2*a* essentially indicates only the presence of the radio frequency component. This may be regarded as a modulated radio frequency output signal which could be immediately useful for carrier-current or radio transmission.

The structure of **10** may be successfully produced by many of the known semi-conductor processes and from many of the known materials which are capable of providing semi-conductor junctions. Since high resistances are desired in the upper layer **12** and the central layer **14**, silicon is a particularly desirable material because of its high resistivity. In one instance, a successful structure was formed of NPN silicon material having an upper N layer about 0.00025 inch thick and having a resistivity of about ten ohm centimeters, a central P layer 0.0005 inch thick and having a resistivity of about twenty ohm centimeters, and a bottom N layer of 0.006 inch thick and a resistivity of ten ohm centimeters. In this structure the upper two layers were epitaxially grown onto the lower N layer. In another embodiment, each of the three layers had a thickness of approximately 0.0015 inch. In this case, the structure was produced by diffusion of phosphorous into the outer surfaces of a P type silicon structure to the required depth to provide N regions and the resultant PN junctions. The diffusion may be accomplished by conventional diffusion techniques. With the last-mentioned structure, having an upper layer thickness of 0.0015 inch, incident radiation having a wavelength of 8900 angstroms and higher penetrates the upper silicon layer to the upper junction quite efficiently.

Almost any of the known semi-conductor materials may be employed in the present invention, including the compound semi conductors such as gallium arsenide and cadmium diarsenide, as well as the monatomic semi-conductors such as germanium and silicon, and most of the known production methods may be employed for obtaining the desired junctions. However, at the present stage of development of semi-conductor technology, for the structure of FIG. 1 silicon appears to be the best because of its production controllable high resistivity and because of the apparent prospect of producing much higher resistivity.

Among the known processes other than diffusion for producing semi-conductor structures required in the present invention there are the alloying methods. For instance, a semi-conductor such as germanium may have an alloyed layer of metal such as indium applied to the top and the bottom to form fusion junctions with the germanium. This will form a PNP structure. The metal layers may also be formed by electrolytic deposition—having the advantage of low temperature formation to preserve the high resistivity of the semi-conductive central layer. The metallic upper layer must be thin enough to provide the desired resistance for the voltage divider and to admit the radiation to the junction. While the above descriptions relating to FIGS. 1, 2 and 3 were in terms of the use of an NPN structure, it will be apparent that by reversing the polarities of the operating voltages, a PNP structure may be employed with equal facility. It is also clear that various other heterojunction structures employing different materials in the different layers, which may be of the same conductivity type, but which nevertheless have the ability to form asymmetrical junctions, are useful in this invention.

An interesting combination of materials exists where the outer layer which is exposed to radiation can be chosen so that it is substantially transparent to the radiation and the central layer is opaque. In this instance, the operation of the device is very efficient because the radiation is all substantially absorbed in the junction. An example of this class of structures is one employing gallium arsenide as the outer layer and germanium as the material of the central layer. This is an example of a heterojunction since both materials are of N conductivity type, but they nevertheless form a radiation sensitive asymmetrically conductive semi-conductor junction.

The different layers **12**, **14** and **16** may be referred to in this specification as being comprised of different materials. It will be understood that differences between the materials of these different layers is only that difference which is required for the purpose of producing an asymmetrically conductive semi-conductor junction. Thus, the layers may differ only in conductivity type such as P and N type silicon, or both may be of the same conductivity type but composed of different molecules such that asymmetrically conductive junctions are produced. Greater differences may also exist. For instance, the different layers may be of different semi-conductors of different conductivity types, or a semi-conductor plus a junction-forming metal. Thus, the term "semi-conductor junction," as used in this specification, refers to a joint or contact between different materials, as least one of which is a semi-conductor. It is not necessarily a junction between semi-conductors, or between different conductivity type semi-conductors. This broad category is sometimes referred to as "contacts" rather than "junctions."

The upper layer which is exposed to radiation is preferably thin enough so that the radiation is capable of producing "hole-electron" pairs at the upper junction. This may occur even without penetration of the radiation to the junction, as long as the hole electron pairs are created in the upper layer in the near vicinity of the junction. The radiation may also be applied to the edge of the structure to reach the junction directly without traversing the upper layer.

One of the most interesting aspects of this invention is that it is basically a low voltage device. For instance, with the structure of FIG. 1 satisfactory operation is achievable with a voltage gradient across the upper layer of no more than five to ten volts per inch. This presents many advantages including safety, and the possibility of light weight and inexpensive power supplies. Also operation from remote power and control signal sources is much more feasible.

FIG. 4 shows a modification of the embodiment of FIG. 1 in which the intermediate layer **14** of the structure **10A** is discontinuous, being composed of individual bridges of material indicated at **14A** to **14E** between the upper layer **12** and the lower layer **16**. The remainder of the space between the outer layers is simply open. However, it may be filled with insulating material if desired. This modified structure has the virtue that the lateral resistivity of the central layer between individual bridges such as **14A** and **14B** is infinite. However, there is no longer an infinite number of diode pairs and the resolution of the device is dependent upon the spacing of the discrete material bridge "dots." Despite this, high resolutions are attainable, as will be explained below.

The operation of the FIG. 4 embodiment of the invention is directly analogous to the operation of the system of FIG. 1 with discrete beams of radiation as explained in connection with FIG. 3. The embodiment of FIG. 4 is incapable of providing a trace such as that shown in FIG. 2 because the discrete "dots" of central layer material necessarily cause a trace of discontinuous "blips" as shown, even with uniform radiation. However, it should be pointed out that the illustration of FIG. 4 is a simplified and idealized representation of the embodiment having discrete operable portions caused by the discontinuous central layer. It is intended that such a structure shall include a large number of very closely spaced cen-

tral layer material bridges and that the structure shall be proportionately longer than shown. It should be mentioned in this connection that the embodiment of FIG. 1 also is intended to be proportionately longer than shown. In addition to the advantage of infinite impedance in the discontinuities of the central layer, the embodiment of FIG. 4 also provides the advantage that whenever one of the discrete junctions is masked from illumination, it nevertheless causes a "dark current pip" in the output signal as the null voltage condition is achieved. This "pip" provides an indexing signal which serves to precisely determine the state of the sweep operation of the system. Such a pip is illustrated in FIG. 4 at 48.

A successful structure in accordance with FIG. 4 has been produced by employing elongated bars of germanium for the outer layers 12 and 16, and by fusing drops of indium metal between the two pairs in a furnace in order to produce the intermittently spaced material bridges 14A–14E. For this structure, the germanium bars may be about 0.006 inch thick and about 0.010 inch in width, and the "dots" of indium may be approximately 0.005 inch in width. The "dots" may be spaced from 0.035 inch down to 0.010 inch on centers. With this sort of a structure it has been found to be possible to accomplish the scanning function with as little as one quarter of a volt difference in voltage bias between adjacent indium material bridges or "dots." Devices of this type are capable of withstanding maximum voltages in the range from 50 to 200 volts without encountering breakdown. Accordingly, it is possible to provide a structure in accordance with FIG. 4, and with the above materials, having from 200 to 800 indium dots as a maimum. It is obvious from this that with the discontinuous central layer, the scanners of the present invention are capable of extremely high resolution. Apparently, the lateral conductivity of the central layer in the continuous layer version of the invention illustrated FIG. 1 limits the resolution of that device in some respects. Accordingly, this discontinuous central layer embodiment of FIG. 4, when composed of many closely spaced "dots," may provide even higher resolution than certain of the continuous central layer versions of the invention.

As illustrated thus far, the scanners of the present invention are essentially capable of scanning only a line, and not an area. However, it will be apparent that the line scanners may be employed to scan areas by providing for relative movement between the scanner and the area pattern to be scanned. Thus, the line scanner will provide information about the entire area by looking at the area as a succession of lines which are scanned in sequence. It is possible also to provide a line scanner structure which is capable of scanning an area by building the structure in a zig-zag pattern so that it scans back and forth over the whole area without the necessity for relative movement between the scanner and the pattern to be scanned. Various other line scanning patterns or shapes may be employed either to scan an entire area, or to simply scan a particular portion of an area. It is also possible to provide a number of line scanners physically arranged in parallel alignment so that each will scan a different portion of the pattern to be scanned. These parallel arranged line scanners can operate simultaneously or in sequence and they may be operated in response to a common control system. Such an arrangement is shown in FIG. 8 and described in more detail below.

FIG. 5 illustrates a partial schematic top view of an area scanning structure which is basically simply a wide version of the structure of FIG. 1. In order to assure that the current is distributed evenly across the upper layer 12G in the structure 10C of FIG. 5, the connections 24 and 26 to the bias voltage source are supplemented by plated electrodes 52 and 54 at the ends of the structure. In essence, therefore, this is an expanded or widened line scanner which is capable of scanning areas. While this area scanner will not provide precise reproduction of a picture, for instance, it will provide sufficiently distinctive scanning signals for purposes such as character recognition so that certain letters or characters can be distinguished from certain others. Rather than scanning from point to point along a single line, as the line scanner does, the area scanner accomplishes the scanning function from line to line across the area between electrodes 52 and 54, these lines being parallel to electrodes 52 and 54. This scanning action may be likened to the movement of a mechanical slit aperture across the area, but in the present invention, this action is obtained entirely by electrical means so that it is very accurate and precise and does not involve any of the problems of acceleration and deceleration of parts such as is encountered with mechanical devices. Thus, the scanner provides precise information on the illumination at each line of the scan. For purposes of clarity, in FIG. 5, the sweep generator 34, the load resistor 32, and the associated apparatus have been omitted. However, it will be understood that these components are to be employed with the embodiment of FIG. 5 and are to be essentially the same as shown in FIG. 1.

FIG. 6 shows another area scanner modification in which the contacts 24 and 26 have been replaced by commutator brushes 24B and 26B. These brushes are arranged to make contact with plated electrode spots 56 on the upper surface of the modified structure 10D. The operation of the system again is similar to that of FIG. 5 except that the patterns of equal potential conditions existing across the upper layer of the structure 10D are as indicated by the dotted equal potential lines 58. This gives still a different scanning pattern which is particularly useful in detecting the presence of certain characters or shapes such as in character recognition. Preferably, the brushes 24B and 26B are mounted and supported on a rotatable yoke 59 so they can be rotated together to provide for scanning operation along different diagonal directions on the structure 10D. These variations in direction are also very useful in making successive scans for accomplishing the character recognition function.

Alternatively, electronic switching may be employed to switch the bias voltage to different opposed pairs of conductive spots 56 in the structure of 10D so as to establish different diagonal directions of scan. Also, the pattern of equal potentials across the structure 10D may be modified by applying bias voltages to several pairs of spots simultaneously and by suitably adjusting these voltages in order to obtain output signals indicative of different patterns of scan.

FIG. 7 is a schematic representation of another modification of the invention which is capable of providing a circular scan in which the bias potential is applied between an outer ring electrode 60 and a central electrode 62 on the structure 10E. The resultant circular pattern scan is particularly valuable for identifying closed characters such as the letter "D," the letter "B," or the digit "0." It will be apparent from FIGS. 6 and 7 that there is an almost infinite variety of special purpose scanning structures which may be built up from modifications or combinations of the structures shown. For instance, a double circular scan structure can be provided for the special purpose of identifying characters having upper and lower closed portions, such as the letter "B," and the figure "8." Such a structure is also useful for detecting the presence of a single closed portion in the upper character region, such as occurs in the capital letter "A" or the capital letter "R," or in the lower character region such as in a lower case letter "b" or in number the "6."

In FIGS. 6 and 7, as in FIG. 5, the sweep generator 34 and the load resistor 32 and the associated apparatus have again been omitted, but are understood to be present in the actual embodiments.

FIG. 8 shows an area scanning system in accordance with the present invention and employing a plurality of

line scanners indicated at 10G through 10M. These scanning structures are physically arranged in parallel alignment for the purpose of individually scanning different columns of a punched card 72, the opposite surface of which is illuminated by a light source indicated at 74. The structures 10G through 10M are supplied from a common bias supply source schematically illustrated at 22G and the other end of the common bias circuit includes the resistor 28G and the associated connection to ground. The sweep voltages to the structures 10G through 10M are provided through the respective load resistors 32G through 32M from a delay line 76. The sweep voltages are obtained from a conventional sweep voltage generator 78 in response to a triggering pulse applied to the sweep generator at 80 from a remote control line 82. When it is desired that the information be obtained from the system of FIG. 8, a trigger pulse is sent from the remote control station through the connection 82 to trigger the sweep generator 78. The sweep pulse travels down the delay line 76 and sequentially causes the sweep operation at each of the scanning structures 10G through 10M. The resultant output signals are then supplied through the capacitors indicated at 84 through 94, and the blocking diodes indicated at 96 through 106 to a common output line 108. From the output line 108, these signals are applied to an amplifier 110 which in turn provides amplified output signals to the signal line 82 so that the information is transmitted back to the central control station. This system is very simple and inexpensive since it requires only a single pair communication line for the purpose of communicating between the remote central control station and the scanning apparatus, and since a very minimum of equipment and power supply is required at the scanning location.

It will be obvious that other modifications of the system of FIG. 8 are possible. For instance, it may be desirable in some instances to provide a separate sweep generator for each of the scanner structures 10G through 10M. It may also be desirable in some instances to employ a commutator device different from the delay line 76.

While only six of the scanner structures 10G through 10M are shown in FIG. 8 for scanning six columns, it will be understood that the system may be easily extended to any desired size, such as including apparatus sufficient to scan the entire eighty columns of a conventional punched data card. It will be understood also that the system of FIG. 8 is very useful for optical scanning of almost any rear radiation source, the punched card being shown in FIG. 8 only for purposes of illustration.

The radiation sensitive structure 10 of FIG. 1 may be constructed so that it is symmetrical about the intermediate layer 14. It will be obvious then that the lower juncion 20 formed between the intermediate layer 14 and the lower layer 16 may be constructed so that it is photosensitive, or sensitive to non-visible radiation. Thus, either the upper junction 18 or the lower junction 20 may be radiation sensitive, or both of these junctions may be radiation sensitive and both may be arranged to receive radiation signals.

Referring back to FIG. 3 and recalling the explanation of operation accompanying FIG. 3, it will be clear that if the lower junctions 20A through 20E are illuminated instead of the upper junctions 18A through 18E, then the sweep voltage from generator 34 will actually cause the diode pair 18E, 20E to turn on rather than turning off after the null voltage condition and reversal of bias is achieved. There will then follow in succession the turning on of the succeeding illuminated diode pairs. The current change signals detected by the network 36 and the oscilloscope 38 will be essentially the same as they are for illumination of the upper junctions. (A similar result is achieved if the sweep voltage is reversed so that diode pairs are turned on rather than off when the upper layer is illuminated.)

If both junctions are illuminated, then a double amplitude signal is provided to the oscilloscope 38. Accordingly, in a system where discrete radiation beams such as beams 40 of FIG. 1 are used or in the discrete diode version of FIG. 4 in which the intermediate layer is discontinuous, by illumination of both sides of the radiation responsive structure 10, a comparison of the information on the upper and lower sides is possible. Thus, where beams on the upper and lower surfaces coincide, a double amplitude signal results, but where coincidence does not occur there is only a single amplitude signal, or no signal if both sides are dark. By employing an output detector which is responsive only to output signals above the single amplitude, only the coincidence signals appear at the output. Such a modification of the system of the present invention has obvious advantages and utility. For instance, conventional punched data cards can be optically compared very rapidly. It may also be observed that if the structure 10 is illuminated on its side edge so that the radiation reaches the junction without having to transverse the upper layer, it is not necessary to mask the junction 20 so that only junction 18 is illuminated. This is true because, as pointed out above, illumination of both junctions will simply enhance the output.

Another interesting feature of the invention is that the current resulting from incident radiation upon each back biased semi-conductor diode portion of the structure is substantially independent of the back bias voltage and is almost entirely dependent upon the intensity of the radiation to which the diode is exposed. This assumes, of course, that the back bias voltage is above the minimum value which is required to initiate conduction. This is an important feature, particularly when the structure 10 is subjected to radiation on both outer layers. This feature is important because it means that changes in current detected at load resistor 32 during scanning are due almost exclusively to the shut-off or turn-on of individual diode pairs as the null voltage condition is passed during the sweep.

One of the important features of the present invention resides in the fact that very little power drain is required from the sweep generator and to the output detector. Accordingly, it is quite practical to locate the sweep generator and the detector portions of the system remote from the radiation responsive structure 10 so that it is possible to use the scanner system for remote scanning. With such a physical separation between the location of scan and the location of signal utilization, the system has many uses. One important class of such uses is in the gathering of physical data for process control systems. For instance, the line scanner version can be used to detect the position of the pointer of a meter, or the elevation of a mercury column in a thermometer. Furthermore, if the modification of FIG. 4 is employed for these purposes, then the discrete signals available from the individual diode pairs provide signals which may be regarded as digitized signals. The apparatus then is effective not only to provide a remote electrical indication of the data, but to provide such an indication in digitized form. As prevously mentioned, the digitization can also be accomplished by employing discrete light beams as shown initially for FIG. 1. The light from a single source may be divided into discrete beams for this purpose by means of a perforated mask.

It will be observed that the total bias voltage from source 22 in the embodiment of FIG. 1 should be approximately equal to the maximum amplitude of the sweep voltage available from generator 34 in order to assure that the entire device 10 is scanned. It is an interesting feature of this invention that these voltages need not have precisely determined values as long as there is a reasonable degree of correlation between the two voltages, an as long as the voltages are sufficient to provide operation of all of the diode pairs within the

device 10. Since these voltages may be allowed to vary rather widely, as long as they are correlated in amplitude, it is sometimes advantageous to supply both voltages from a single source. Thus, the bias voltage available from source 22 in FIG. 1 may be provided instead from a square pulse wave generator, and the same square pulse wave may be supplied also to a suitable network to provide a sweep voltage for use in place of the sweep voltage source 34. This suggests the further possibility that the source of the square wave voltage may be quite remote from the scanning structure 10 and the operation of the device will obviously be satisfactory despite variations in transmission losses of the square wave signal which serves to provide both the bias voltage and the sweep voltage.

Another important feature of the present invention is that the scanning apparatus is responsive to a rather wide range of radiation intensity. This may be described also as "gray scale" sensitivity. The gray scale terminology is employed because it signifies an ability to distinguish not only between black and white, but also an ability to distinguish grays. It has been discovered, for instance, that with one physical embodiment, it is possible to detect various gradations of light intensity generally in the range from somewhat less than 100 footcandles to more than 1,000 footcandles with an incandescent tungsten filament as the light source.

In all of the embodiments of the invention, the output detection system has been indicated as consisting of the load resistor 32, network 36, and a cathode ray oscilloscope 38. The cathode ray oscilloscope 38 may be of any conventional commercially available type and therefore it is not shown in detail here. Typically, the load resistor 32 may be in the range from 50 to 100 ohms, the capacitor of network 36 may have a capacity in the order of 0.0015 microfarad, and the resistor in network 36 may have a value in the order of 1,000 ohms. While the final output device of the detection apparatus is shown as a cathode ray oscilloscope, in each of the embodiments, it will be understood that other more elaborate detection apparatus may be employed to receive the output from the scanner system. For instance, the series of pulses, or the current change signals may be supplied directly to the input of a computer to accomplish various logical results in response to the scan signal. Also, the scanner, or a combination of scanners may be arranged to scan an area, and the output signals may be supplied to an electronic picture reproduction system including a conventional television picture tube so that an exact visual reproduction of the area which is scanned may be produced. Thus, the invention may be used as a television camera.

All of the above explanations of the operation of this invention have emphasized the detection of transient signals such as are available through the network 36. However, it should be emphasized that useful information may be obtained from the system of the present invention by detecting other characteristics of the voltage appearing across the resistor 32 resulting from the current therein. Thus, the total current at any particular time is a measure of the illuminations striking that portion of the scanning structure containing diode pairs which are not biased off. It is also apparent that the transient signals may be detected by means other than resistor 32 and network 36. For instance, a transformer may be employed to inductively couple the output detector such as oscilloscope 38 to the load circuit including contact 30. The transformer primary winding may take the place of resistor 32.

An interesting feature of the present invention resides in the discovery that greatly improved resolution is available from the apparatus when the scanning structure 10 achieves an elevated temperature in the order of 100° C. This result has been observed particularly with silicon scanning structures. It is believed that the elevated temperature somehow enhances the hole-electron pair activity resulting from the incident radiation. Accordingly, the heat which is generated within the structure 10 by reason of the bias voltage across the outer layer 12 and the resulting current therein, does not create any problems. On the contrary, the heat is advantageous and the design of the structure 10 is preferably made to adjust the heat dissipation capabilities to provide a steady state operating temperature in the order of 100° C.

The operation of the scanners in accordance with the present invention is enhanced by the application of conventional lens coating materials such as silicon monoxide. This coating should preferably be in the order of one-quarter of a wave length of the light with which the scanner is to be employed.

Another interesting aspect of the present invention is that it is responsive to a wide spectrum of radiation. For instance, it is very responsive to radiation in the infra-red range. This is a very interesting feature of the invention because infra-red detectors which are commercially available at present, generally require rather high operating voltages. Since the present invention is a low voltage device, it provides the possibility for a portable and safe and inexpensive infra-red detector.

Another interesting feature of the present invention is that it is operable over a wide sweep speed range. There is virtually no lower limit in the sweep speed and in the upper end of the speed range sweep speeds of at least one tenth of an inch per microsecond are attainable. This corresponds to a read-out rate of one million spots per second. Thus, the apparatus is extremely fast in operation where speed is required, but is capable of operation at almost any speed without impairment in accuracy.

As indicated, above almost any of the combinations of materials which are useful in the production of semi-conductor junctions or contacts which are asymmetrically conductive, are also useful in the present invention. Furthermore, most of the various methods for producing semi-conductor junctions are also useful in the production of the structures 10 of the present invention. Many of these structures and methods, and many other applicable teachings with respect to semi-conductors are to be found in the Handbook of Semiconductor Electronics, by Lloyd P. Hunter, Second Edition, published by McGraw-Hill Book Company in 1962.

In the embodiments employing a semi-conductor for the top layer 12, the semi-conductor material of the top layer is often photoconductive. This means that the reduction in the resistance of illuminated portions of the top layer are reduced in resistance so as to modify the operation of the top layer as a voltage divider. The result is a distortion of the scan because the scan will proceed more rapidly across the illuminated areas and more slowly across the dark areas. This distorts the trace which is produced such that the dark areas appear wider and the illuminated areas appear narrower, and at the same time have an enhanced signal amplitude. The enhancement of the signal is caused by the increased speed of sweep across the illuminated area. For some purposes these distortions of the output are advantageous since they actually improve sensitivity without destroying the usefulness of the desired information. If the distortion is excessive and is not desired, it can be limited or eliminated by different material choices and by different physical geometries.

The above problem of distortion of the voltage divider gradient, as well as distortion of the voltage gradient from other causes, may be avoided or minimized for precision purposes by applying a series of graded voltage values to spaced points along the upper layer 12 so as to clamp those points and more definitely determine the geometry of the voltage gradient. With such a modified structure, the shape of the voltage gradient may be adjusted at will and the speed of scan may be purposely modified if desired. For instance, the voltage gradient between two of such connections may be reduced to sub-

stantially zero so that the scan actually skips the space between such connections. However, if the skipped space is illuminated a large transient vertical trace will occur. This can be ignored because it occurs with such a short portion of the sweep.

While not shown in any of the embodiments illustrated in the drawings, it is possible to connect a control electrode to the intermediate layer 14 of the continuous intermediate layer versions of the invention as illustrated in FIG. 1. Such an electrode may be provided with a gate control voltage which is effective to turn off the scanner if such inhibition is desired. When the device is to be active again the gate voltage is removed from the intermediate layer. The preferred gate voltage polarity is negative for an NPN structure and positive for a PNP structure. If desired, the gating signal applied to the intermediate layer may be an A.C. signal and the output signals are then in the form of a combination of the A.C. and the signal otherwise available from the scanning device. This is effectively a modulated alternating current. It has also been discovered that with certain of the structures 10, in accordance with the present invention, the resolution of the scanner may be improved by simply connecting the intermediate layer 14 through a resistor to ground. It is also possible to provide a modified scanning structure in which the intermediate layer 14 acts as the voltage divider rather than the upper layer 12. However, this arrangement is not believed to be as desirable as the above described embodiments of the invention because it involves a substantial increase in energy losses, and distortion of bleeder voltage distribution.

Another interesting modification of the invention involves the application of an alternating voltage signal in series with the bias voltage source 22. It has been determined that this substantially enhances the output signals available from the scanner. Apparently, as the null D.C. bias voltage condition is achieved at each diode pair, the A.C. impedance of the diode pair is substantially reduced. Accordingly, the switching action within the scanning structure 10 for the alternating voltage is such as to cause a modulation of the A.C. This is a very valuable feature where the system is to be employed as a remote scanner, or where the information obtained from the scanner is to be transmitted over a long distance, because the information may be provided immediately from the scanner as a modulated radio frequency signal which is suitable for immediate transmission through a conventional radio communication or carrier current channel. This mode of operation is not to be confused with that described above in connection with FIG. 2*a* where the A.C. signal is applied to the lower layer 16. However, the alternating current here may be again preferably a radio frequency such as 200-kilocycles.

The term "elongated" is employed in this specification to help define the shape of the scanning structure 10. As used here, this term is intended to emphasize the lateral dimension of the structure parallel to the semi-conductor junctions 18 and 20 and between connections 24 and 26. This is a characteristic which is present not only in the line scanner versions of the invention, such as shown in FIG. 1, but also in the area scanning versions such as shown in FIGS. 5, 6, and 7. Thus, the term "elongated," is intended to refer to the area scanning structure 10C, 10D and 10E, as well as to the line scanning structures such as 10 and 10A. Therefore, this term, as used here, does not necessarily imply that the structure is narrow in both of its other dimensions.

While the invention has been particularly shown and described with reference to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and the scope of the invention.

What is claimed is:

1. A radiation scanner comprising:
(a) an elongated multiple layer structure including an intermediate layer of semi-conductive material of a first conductivity type and two outer layers of semi-conductive material of a second conductivity type, the said layers having asymmetrically conductive semi-conductor junctions therebetween, said junctions having oppositely poled asymmetry and at least one of which has conductive properties responsive to radiation incident thereon;
(b) means connecting one of said outer layers at laterally spaced positions thereon to sources of different bias voltage levels to establish a potential gradient in the layer extending parallel to the said junctions;
(c) means for connecting the other outer layer to another source having a different value of bias voltage;
(d) means for applying a time variant potential difference across the said two outer layers in a direction perpendicular to the said junctions;
(e) a means connected in circuit between said outer layers for detecting functions of the current between said outer layers.

2. A radiation scanner for scanning an area comprising:
(a) an elongated multiple layer structure having a substantial width and including an inner layer of semi-conductive material of a first conductivity type and two outer layers of a semi-conductive material of a second conductivity type, the said layers having asymmetrically conductive semi-conductive junctions therebetween, said junctions having oppositely poled asymmetry and at least one of which has conductive properties responsive to radiation incident thereon;
(b) means connecting one of said outer layers at laterally spaced positions thereof to sources of different bias voltage levels thereon to establish a potential gradient in the layer extending parallel to the said junctions;
(c) means connecting the other outer layer to a source of another bias voltage level;
(d) means for applying a sweep voltage difference between said outer layers; and
(e) means connected in circuit between said outer layers for detecting functions of the current between said outer layers.

3. The area scanner as set forth in claim 2 in which the means connecting one of said outer layers to sources of different bias voltage are so disposed with respect to said layer as to establish a uniform potential parallel to the width of the body and a gradient parallel to the length thereof to define a substantially rectangular scanning area.

4. The area scanner as set forth in claim 2 in which the means connecting one of said outer layers to sources of different bias voltage are so disposed with respect to said layer as to establish a radial potential gradient with equi-potential regions having a common radius, so as to define a circular scanning pattern of controllable radius.

5. A radiation scanner comprising:
(a) a first layer of semi-conductive material of a first conductivity type;
(b) a plurality of discrete bodies of semi-conductive material of a second conductivity type joined to said layer to form therewith a plurality of discrete radiation responsive asymmetrically conductive semi-conductor junctions;
(c) a second layer of semi-conductive material of a first conductivity type joined to said discrete bodies of semi-conductive material to form therewith a plurality of discrete asymmetrically conductive semi-conductor junctions oppositely poled with respect to the junctions of said bodies with said first layer;

(d) means for establishing a potential gradient in said first layer extending parallel to the direction of the said junctions with said bodies, so as to provide a discretely different bias potential at each of the said junctions with said bodies;

(e) means for providing a uniformly distributed time variant bias in said second layer; and

(f) means for detecting the current flow absorbed by said second layer.

6. A radiation intensity scanner comprising:

(a) a plurality of pairs of unidirectional current conducting devices, each pair including a radiant energy responsive device and a second device serially connected in opposite conductivity relationship between first and second terminals;

(b) means establishing the first terminal of each different diode pair at a different bias potential level;

(c) means for varying the potential level with respect to time of all of said second terminals in parallel; and

(d) means for detecting the magnitude of the current flow between said first and said second terminals.

7. A radiation scanner as set forth in claim 1 and in which said intermediate layer is laterally discontinuous to thereby form discrete pairs of oppositely poled asymmetrically conductive junctions.

8. A radiation scanner as set forth in claim 7 in which said outer layers consist essentially of germanium, and said discontinuous intermediate layer consists essentially of indium metal.

9. A radiation scanner ructure in accordance with claim 1 in which said elongated multiple layer structure consists essentially of P type silicon with the outer surfaces thereof being diffused with an N type impurity to provide N type silicon outer layers and a P type intermediate layer with PN junctions therebetween.

10. A radiation scanner as set forth in claim 1 in which said intermediate layer consists essentially of germanium and said outer layers consist essentially of indium.

11. A radiation scanner as set forth in claim 1 in which said intermediate layer consists essentially of germanium and said outer layers consist essentially of gallium arsenide.

12. A radiation scanner in accordance with claim 1 including a connection to said intermediate layer, an additional source of control voltage arranged for connection through said last-named connection to said intermediate layer for providing an electrical gating control of the scanner.

13. A radiation scanner as set forth in claim 1 and including an alternating current source connected to one of said layers.

14. A radiation scanner as set forth in claim 1 and further comprising a high impedance radio frequency generator arranged for connection to said last-named outer layer electrical connection.

15. A radiation scanner in accordance with claim 1 which is arranged for control from a remote control station and further comprising input connections for receiving a square pulse interrogation signal from a remote control station, means connected between said input connections and said spaced outer layer connections for providing said spaced outer layer bias voltage levels in response to said square wave interrogation signal and having an amplitude proportional to the amplitude of said interrogation signal, said means for applying a sweep voltage difference between said outer layers being connected to said input connections for operation in response to said square wave interrogation pulse to provide a sweep voltage difference having a maximum amplitude proportional to the amplitude of the interrogation pulse.

16. A radiation scanner for scanning an area in different directions comprising an elongated multiple layer structure having a substantial width and including an intermediate layer and two outer layers substantially defining the entire upper and lower surfaces of said structure, said intermediate layer being joined to both outer layers throughout substantially the entire length and width thereof, the materials of said layers being selected to form an elongated asymmetrically conductive semi-conductor junction at each of the boundaries between the respective layers, said junctions having oppositely poled asymmetry, at least one of said semi-conductor junctions having substantially increased conductivity in response to illumination thereon when in the back biased condition, at least one of said outer layers having a plurality of electrical connections each including an electrode in contact with the outer surface of said layer, said electrodes being spaced around the periphery of said outer layer in diagonally opposed pairs, means for applying bias voltage level differences across said oppositely disposed pairs and for changing said bias voltage differences to provide for optical scanning in different diagonal directions across the area being scanned, the other outer layer having at least one electrical connection arranged to be connected to a source of another bias voltage level, means for applying a sweep voltage difference between said outer layers, and means connected in circuit between said outer layers for detecting nonuniform changes in the current between said outer layers.

17. An optical scanner comprising an elongated multiple layer semi-conductor crystal structure including an intermediate layer of one conductivity type and two outer layers formed by diffusion of conductivity type determining impurities therein to define said layers as regions of different conductivity type extending throughout substantially the entire length of said structure, said outer layers forming elongated asymmetrically conductive semiconductor junctions with said intermediate layer, said junctions having oppositely poled asymmetry, at least one of said semi-conductor junctions having photoconductive properties when back biased, at least one of said outer layers having electrical connections at laterally spaced positions thereon arranged for connection to sources of different bias voltage levels to thereby establish a voltage gradient thereacross, the other outer layer having at least one electrical connection arranged to be connected to a source of another bias voltage level, a source of sweep voltage connected to said last-named connection, and a transient voltage output signal detector connected to said last-named connection and operable for detecting changes in the current between said outer layers occurring at a rate above that corresponding to a pre-determined frequency.

18. An optical scanner comprising a plurality of elongated multiple layer structures arranged in parallel alignment to scan an area, each of said structures including an intermediate layer and two outer layers substantially defining the entire upper and lower surfaces of said structure, said intermediate layer being joined to both outer layers throughout substantially the entire length thereof, the materials of said layers being selected to form an elongated asymmetrically conductive semi-conductor junction at each of the boundaries between the respective layers, said junctions having oppositely poled asymmetry, at least one of said semi-conductor junctions having photoconductive properties when in a back biased condition, one of said outer layers having electrical connections at opposite ends thereof and arranged for connection to sources of different bias voltage levels to thereby establish a voltage gradient within said layer between said connections, a common source of bias voltage potential connected to all of the said bias voltage connections of all of said multiple layer structures, the other outer layer of each of said scanner structures having at least one electrical connection arranged to be connected to a source of another bias voltage level, each of said last-named connections including connections to a common commutating device, a sweep voltage generator connected to supply a sweep voltage to said commutating device and

through said commutating device to said last-mentioned connections of said respective structures in succession, a signal transmission line connected to said sweep generator for actuation thereof, a separate signal output circuit connected to each of said last-named electrical connections of said structures, each of said output circuits including a capacitor and a blocking diode and being connected in common with each of the other output circuits, an amplifier connected to receive signals from said common output connection, said amplifier being connected to provide said amplifier output signals to said signal transmission line.

19. An optical scanner comprising an elongated multiple layer semi-conductor structure comprising two outer layers of materials of a first conductivity type defining upper and lower surfaces of said structure and an intermediate layer of material of a second conductivity type which is different from said first conductivity type, said intermediate layer being joined to both outer layers to form an elongated semi-conductor junction at each of the boundaries between the respective layers, said junctions forming laterally elongated oppositely poled diodes, at least one of said outer layers having electrical connections at opposite ends thereof arranged for connection to sources of different bias voltages for operation of said layer as a voltage divider, the other outer layer having at least one electrical connection arranged to be connected to a source of another bias voltage level, at least one of said outer layers being arranged to receive optical illumination to be scanned, means for applying a sweep voltage difference between said outer layers, and means connected in circuit with one of said outer layers for detecting abrupt changes in current therein between said outer layers.

20. An optical scanner comprising an elongated multiple layer high resistivity silicon crystal structure including an intermediate layer of one conductivity type and two outer layers formed by diffusion of conductivity type determining impurities therein to define said layers as regions of different conductivity type extending throughout substantially the entire length of said structure, said outer layers forming elongated rectifying semi-conductor junctions with said intermediate layer, said junctions being oppositely poled, said structure being arranged to receive illumination at one of said outer layers and operable to provide hole-electron paris at the adjacent junction in response thereto, at least one of said outer layers having electrical connections at opposite ends thereof arranged for connection across a source of bias voltage to thereby establish a voltage gradient therein, the other outer layer having at least one electrical connection arranged to be connected to another bias voltage level source, a source of sweep voltage connected to said last-named connection, and a transient voltage output signal detector connected to said last-named connection and operable for detecting changes in the current between said outer layers occurring at a rate above that corresponding to a predetermined frequency.

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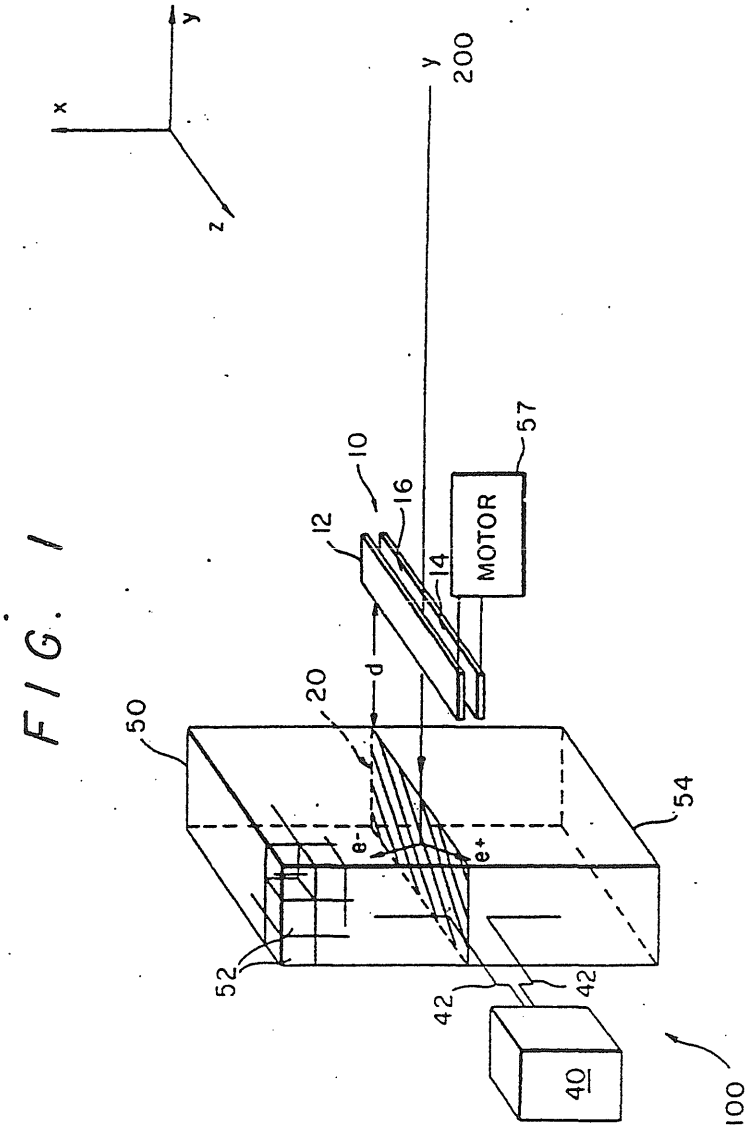
FIG. 1



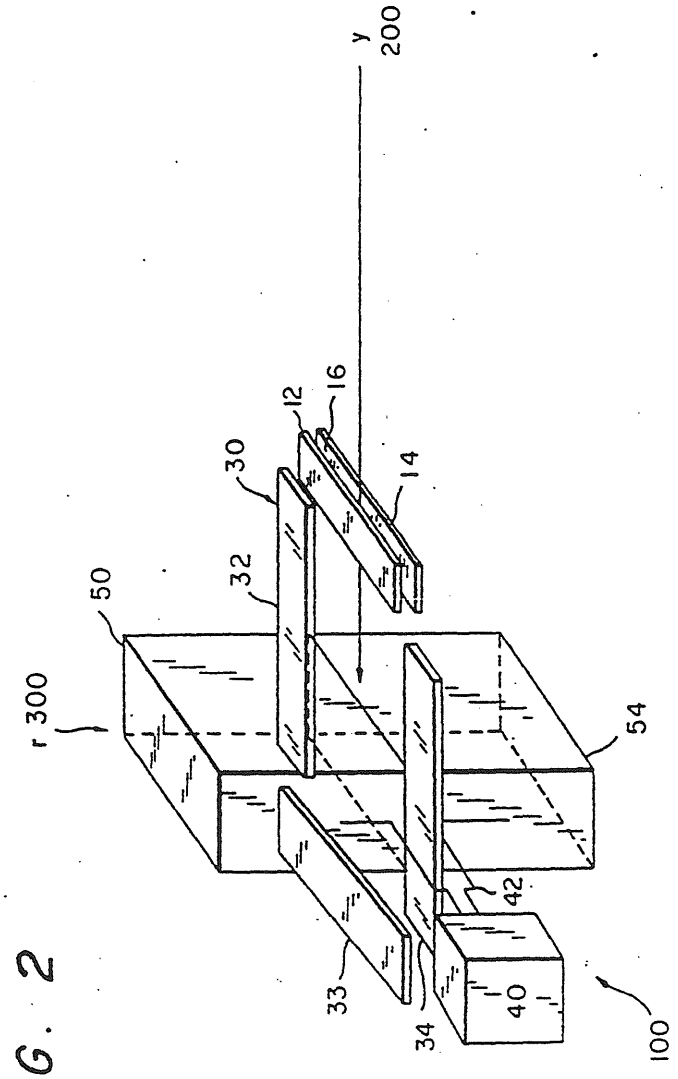
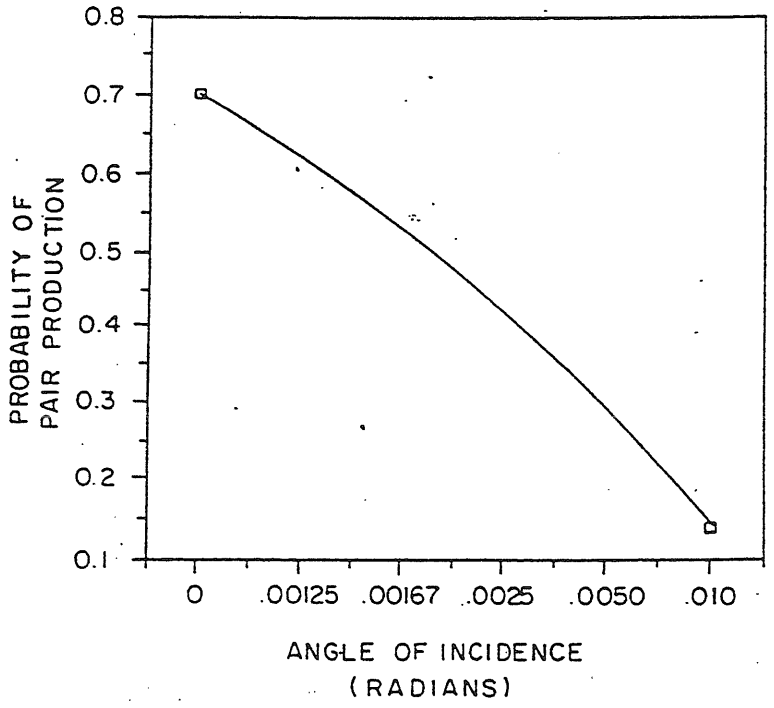


FIG. 2

FIG. 3


0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
PROBABILITY OF PAIR PRODUCTION
0
.00125
.00167
.0025
.0050
.010
ANGLE OF INCIDENCE (RADIANS)

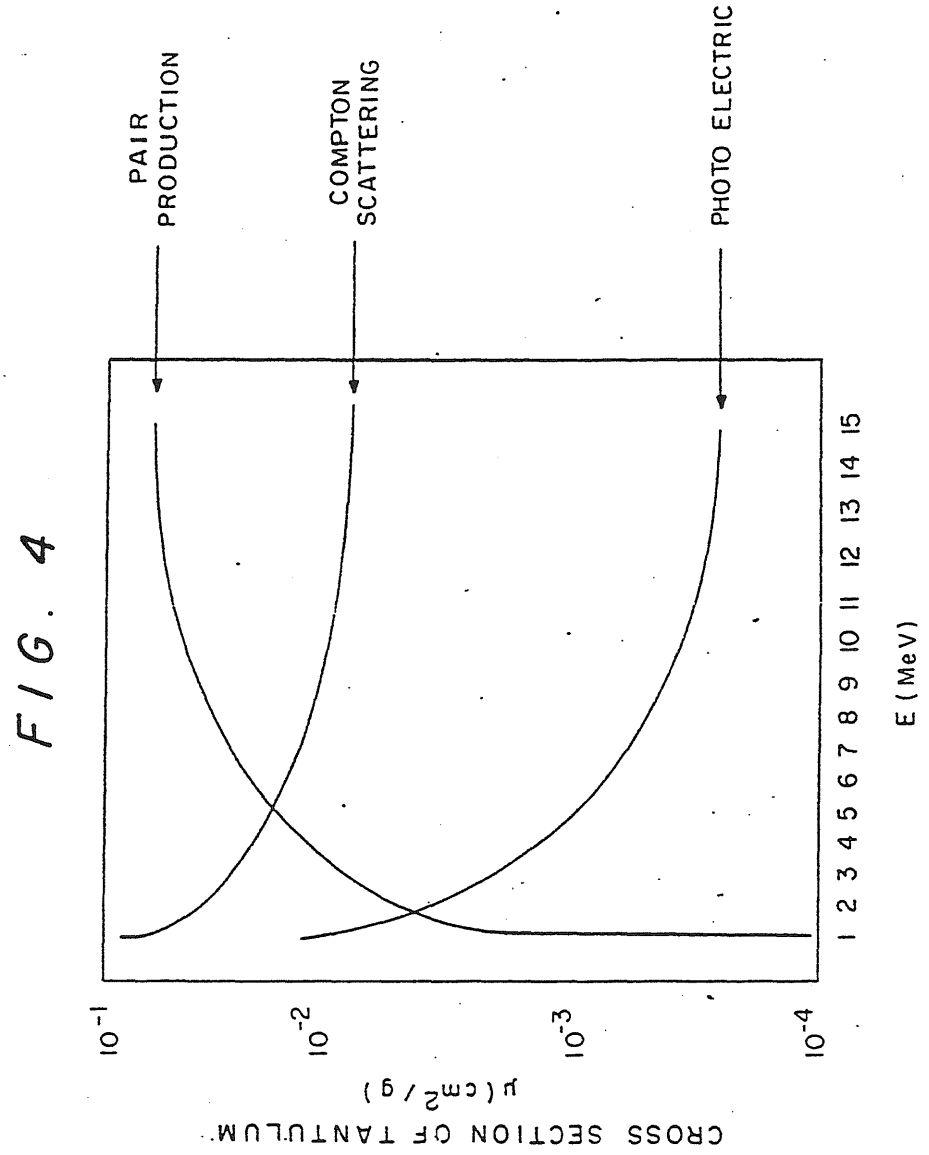

PAIR PRODUCTION
COMPTON SCATTERING
PHOTO ELECTRIC
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
E (MeV)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
μ (cm²/g)
CROSS SECTION OF TANTULUM

FIG. 4

United States Patent [19]

Zigler et al.

[11] Patent Number: 4,954,709

[45] Date of Patent: Sep. 4, 1990

[54] **HIGH RESOLUTION DIRECTIONAL GAMMA RAY DETECTOR**

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[73] Assignee: Apti, Inc., Washington, D.C.

[21] Appl. No.: 394,331

[22] Filed: Aug. 16, 1989

[51] Int. Cl.[5] G01T 1/29; G01T 7/00

[52] U.S. Cl. 250/385.1; 250/374; 250/389; 250/394

[58] Field of Search 250/374, 385.1, 389, 250/394

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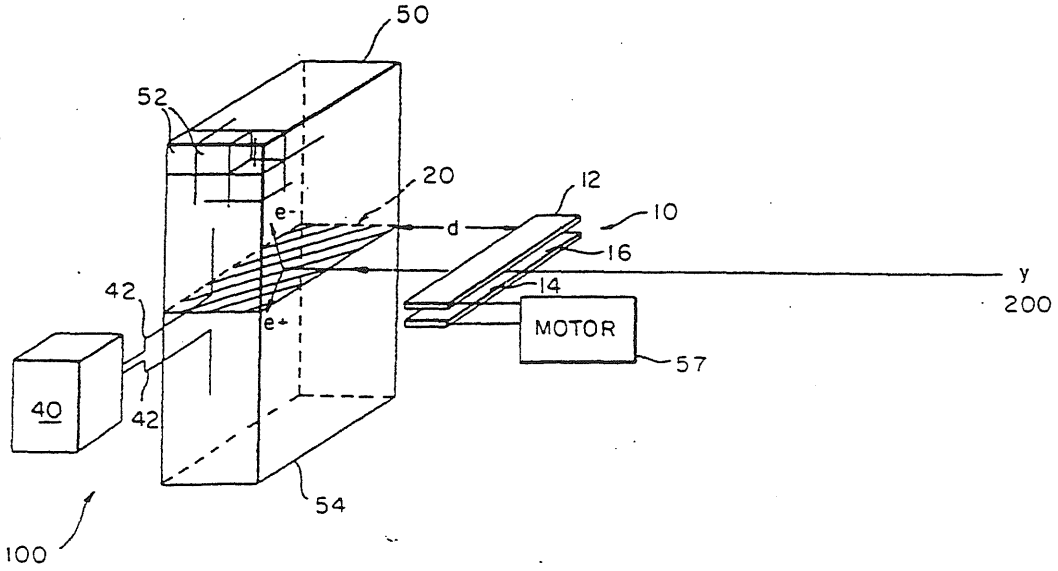
[57] ABSTRACT

A high resolution directional gamma ray detector includes a thin piece of foil, such as tantalum, which reacts with gamma rays incident to the edge of the foil to generate electron/positron pairs. Gamma rays originating from directions other than a direction of interest are shielded from the foil by shielding plates. An opening between the foil by shielding plates. An opening between two collimating plates permits passage of gamma rays originating from a direction of interest and allows gamma rays originating from a direction of interest to react with the foil. The generated electron and positron cause ionization in a plurality of cells. Signals resulting from these ionizations are processed by an electronic computation system through the use of coincidence processing to determine whether the signals are the result of a reaction between the foil and a gamma ray which passed through the collimator opening.

14 Claims, 4 Drawing Sheets



HIGH RESOLUTION DIRECTIONAL GAMMA RAY DETECTOR

BACKGROUND OF THE INVENTION

The present invention relates to gamma ray detectors. More specifically, the present invention is related to light weight directional gamma ray detectors having a high degree of angular resolution, high efficiency, and an ability to discriminate low energy gamma rays.

Conventional directional gamma ray detectors generally employ the use of extended collimators and shielding to channel gamma rays from a predetermined direction to the measuring device of the gamma ray detector. An example of a conventional direction gamma ray detection system is illustrated in U.S. Pat. No. 3,562,526 issued to Lawson. The detection system disclosed in this reference employs a shield having a plurality of passages extending in parallel relationship with one another to collimate incoming gamma rays, and requires a great deal of space and weight due to the extensive use of shielding material and the construction of the collimator. The detection system disclosed in U.S. Pat. No. 3,562,526, therefore, is impractical in the many applications where space or weight is a concern.

Another type of conventional directional gamma ray detectors is illustrated U.S. Pat. No. 4,136,282 issued to Cox et al. The detector disclosed in U.S. Pat. No. 4,136,282 employs a radiator strip contained within a case that is made of an electrical conductor of a high atomic number that is backed by a conducting strip of a low atomic number. In operation, gamma rays incident normal to the broad side of the radiator will pass through the junction of the radiator strip and conducting strip causing electrons to be freed as a result of three processes, the photoelectric effect, the Compton effect and pair production. The electrons produced by the photoelectric effect in the radiator strip and conducting strip are emitted from the radiator strip and collected by the case. The current in the case is measured to determine the magnitude of incident gamma rays.

The above-described detector, while having a degree of directional sensitivity, does not provide a high degree of angular resolution, i.e., an angular resolution on the order of approximately 0.1 radian or less. In addition, the above-described detector does not discriminate low energy gamma rays, that is, gamma rays below 1 MeV. Since environments where a gamma ray detector may be used frequently have a large number of low energy background gamma rays, discrimination of these low energy gamma rays is essential in order to eliminate unwanted detection signals. Other conventional directional gamma detectors, for example as disclosed in U.S. Pat. No. 4,259,575, also suffer from the lack of a high degree of angular resolution. Thus, extensive collimators or shielding are still needed in order to obtain a high degree of angular resolution, thereby adding to the weight and physical size of the detector.

Thus there is a need for a lightweight, compact and highly sensitive directional gamma ray detector which has a high degree of angular resolution and which can function effectively in an environment having a large number of low energy background gamma rays.

SUMMARY OF THE INVENTION

An object of the invention, therefore, is to provide a highly sensitive directional gamma ray detector with a high degree of angular resolution.

Another object of the invention is to provide a directional gamma ray detector which is lightweight, compact and contains a minimum amount of shielding material.

An additional object of the invention to provide a directional gamma ray detector which is insensitive to background gamma rays below 1 MeV.

A still further object of the invention to provide a directional gamma ray detector whose angular resolution may be adjusted.

More specifically, the present invention provides a directional gamma ray detector including a thin piece of foil material which reacts with high energy gamma rays incident to the edge of the foil to generate electron/-positron pairs. Gamma rays originating from directions other than a direction of interest are shielded from the foil by a shielding material. The shielding material, however, can be extremely thin and light weight due to the thickness of the foil, i.e., only the thin edge of the foil needs to be shielded as gamma rays incident the broad surface of the foil will pass through the foil with a low probability of generating electron/positron pairs. A collimator is provided with a collimator opening which permits passage of gamma rays originating from a direction of interest. The collimator is also relatively small and light weight due to the width of the foil. The electron and positron that result from the reaction with the foil pass through gas cells and generate signals indicative of their direction. These signals are processed by an electronic computation system to determine whether the signals are the result of a reaction between the foil and a gamma ray which passed through the collimator opening.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is described below with reference to the accompanying drawings, where:

FIG. 1 illustrates a high resolution directional gamma ray detector according to a preferred embodiment of the invention, with shielding removed for clarity;

FIG. 2 illustrates the high resolution directional gamma ray detector of FIG. 1 with the shielding included;

FIG. 3 is a graph of the probability of electron/positron pair production versus the gamma ray angle of incidence; and

FIG. 4 is a graph of the cross section of a tantalum foil versus gamma ray energy.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIGS. 1 and 2 illustrate a preferred embodiment of a high resolution directional gamma ray detector 100. Shielding has been removed from FIG. 1 to more clearly illustrate the generation of electron positron pairs in response to incident gamma rays. The high resolution directional gamma ray detector 100 includes a thin piece of foil 20 located between a first multicell gas chamber 50 and a second multicell gas chamber 54. The first multicell gas chamber 50 and the second multicell gas chamber 54 include a plurality of individual gas cells 52 that are electrically connected to an electronic computation system 40 via a plurality of signal lines 42.

A collimator 10 is located in front of the foil 20 and includes collimating plates 12 and which are driven by a motor drive system 57. As shown in FIG. 2, first, second and third shielding plates 32, 33 and 34 are located adjacent to and coplanar with the metal foil.

In operation, a gamma ray originating from a direction of interest 200 passes through collimator 10 and reacts with foil 20. The foil 20 is oriented such that a gamma ray 200, passing through the collimator 10, will have a path through the foil 20 that maximizes the chance of a reaction that will generate an electron/positron pair, i.e., a gamma ray which passes through the collimator 10 will be exposed to a sufficient amount of foil material to make a reaction likely. As illustrated in FIG. 1, gamma rays passing through the collimator 10 preferably strike the edge of the foil 20.

The first collimating plate 12 and the second collimating plate 14 form a collimator opening 16 through which the gamma ray from the direction of interest 200 passes. The first collimating plate 12 and the second collimating plate 14 are parallel to each other, have dimensions of $3\times100\times0.15$ centimeters and are preferably fabricated from tantalum or tungsten, although other dimensions and materials may be used. Gamma rays which do not originate from a direction lying in the plane of the collimator opening 16 will be attenuated prior to reaching the foil 20 by the first collimating plate 12 and the second collimating plate 14. Thus only an acceptably low number of gamma rays which do not originate from a direction lying in the plane of the collimator opening will have a chance to react with the foil 20. Thus, the collimator 10 provides directional sensitivity to the directional gamma ray detector 100.

The angular sensitivity of the directional gamma ray detector 100 may be varied by varying the distance d between the collimator 10 and the foil 20. For example, motor drive system 51 or other positioning systems may be employed to move the collimator structure to adjust the distance d. If the distance d is decreased, the directional gamma ray detector 100 will detect gamma rays that originate from a wider range of incident angles than if the distance d is increased. An angular resolution of 0.002 radians in the X direction may be obtained.

When the gamma ray 200 reacts with the foil 20 an electron (e^-) and a positron (e^+) are emitted through the pair production phenomenon. Since momentum must be conserved in the reaction, the electron will be emitted in one direction, the positron will be emitted in another direction, and the paths the emitted electron and the emitted positron will be related to one another by conservation of momentum principles. FIG. 3 illustrates the probability of electron/positron pair production versus gamma ray angle of incidence.

In the preferred embodiment the foil 20 has dimensions of $4\times100\times0.005$ centimeters and is made of tantalum. An advantage of using a material such as tantalum and using electrons and positrons generated as a result of the pair production reaction may be seen from FIG. 4, namely, the pair production cross section of tantalum decreases significantly below 5 MeV and is zero. These small pair production cross sections at low gamma ray energies and the coincidence procedure, to be discussed in further detail below, make the detector insensitive to low energy gamma rays. Since gamma ray detectors are frequently used in environments which have many low energy gamma rays which are of no interest, the use of a foil material and coincidence procedure results in a detector that is insensitive to low energy gamma rays. reduces extraneous reactions and, as will be explained later, reduces unwanted noise.

The use of tantalum makes the directional gamma ray detector 100 sensitive to gamma rays in the 1–30 MeV range. Other foil materials may be used to detect gamma rays up to and above 60 MeV, depending on a user's particular requirements. For example, copper may be employed as the foil 20 to make the directional gamma ray detector 100 sensitive to gamma rays in the 15–60 MeV range.

The shielding plates 32, 33 and 34 shield the foil 20 from gamma rays which are traveling in the plane of the foil 20 and which originate from a direction other than the direction of interest. The first and third shielding plates 32 and 34 preferably have dimensions of $4\times15\times0.15$ centimeters and can be made of tantalum, tungsten, or any other heavy metal attenuating material. The third shielding plate 33 preferably has dimensions of $4\times100\times0.15$ centimeters and can be made of the same type of material as shielding plates 32 and 34.

Due to the geometry of the present invention, only gamma rays traveling in the plane of the foil 20 will encounter enough foil material to make a pair production reaction likely. Therefore shielding only has to be provided in the plane of the foil resulting in a substantial overall weight reduction over conventional detectors. It should be noted that it is possible that a gamma ray incident approximately normal to the foil 20, such as gamma ray 300 illustrated in FIG. 2, may react with the foil 20. Reactions due to gamma rays incident approximately normal to the foil 20 will seldom occur since these gamma rays will pass through very little foil material. In addition, as will be discussed below, reactions resulting from gamma rays incident approximately normal to the foil 20, gamma rays incident at other angles not in the direction of interest, and gamma rays originating within the detector due to Compton interaction in the foil or in the multicell gas chambers can be discriminated by electronic signal processing.

The emitted electron and positron are detected in first multicell gas chamber 50 and second multicell gas chamber 54. In the preferred embodiment, each multicell gas chamber 50 and 54 has dimensions of $6\times10\times100$ centimeters and includes seven hundred fifty gas cells 52. The gas cells 52 each have dimensions of $2\times2\times2$ centimeters and are filled with argon or other high gain ionization gas. When an electron or a positron passes through a gas cell 52, the gas is ionized and a discharge current is produced. The discharge currents from all of the gas cells 52 are routed to electronic computation system 40 via plurality of signal lines 42.

The electronic computation system 40, which is preprogrammed with possible values of input momentum of a gamma ray passing through the collimator, receives the signals from the gas cells 52, determines the path of the emitted electron and the path of the emitted positron, and employs coincidence processing to determine if a gamma ray from the direction of interest has been received. As previously explained, the path of an incident gamma ray and the paths of the emitted electron and emitted positron are related by conservation of momentum, therefore the path of the electron and the path of the positron indicates whether the electron/positron pair was generated as a result of a reaction between the foil 20 and a gamma ray which passed through the collimator 10, i.e., the paths generated from

a gamma ray received from the direction of interest will be mirror images in respect to the plane of the foil.

Coincidence processing also screens out signals resulting from stray ambient electrons and positrons and other particles which may cause ionization in the gas cells 52. The electronic computation system 40 discriminates between gamma rays which pass through the collimator 10 and react with the foil 20, such as gamma ray 200, and gamma rays which do not pass through the collimator 10 but do react with the foil 20, such as gamma ray 300, by determining the paths of the emitted electron and the emitted positron. The electronic computation system 40 also discriminates gamma rays resulting from reactions within the detector.

The foregoing description has been set forth merely to illustrate preferred embodiments of the invention and is not intended to be limiting. Since modification of the described embodiments, incorporating the spirit and substance of the invention may occur to persons skilled in the art, the scope of the invention should be limited solely with respect to the appended claims and equivalents.

What is claimed is:

1. A directional gamma ray detector, comprising:
- a first multicell gas chamber and a second multicell gas chamber, each multicell gas chamber having a plurality of gas cells that generate a signal indicative of an electron or positron passing through the gas cell;
- a reaction foil located between and separating the first and second multicell gas chambers, wherein the foil reacts with gamma rays incident to an edge of the foil to produce electron/positron pairs;
- a shield located adjacent to at least one edge of the foil and having a thickness sufficient to prevent gamma rays originating from a direction other than the direction of interest from reacting with the foil within a predetermined acceptable value;
- a collimator having a collimator opening which permits passage of gamma rays originating from a direction of interest; and
- an electronic computation system coupled to the first and second multicell gas chambers to receive the signals generated from the gas cells.

2. A directional gamma ray detector as set forth in claim 1, wherein the electronic computation system performs coincidence processing to determine whether the signals generated are the result of a pair production reaction between the foil and a gamma ray which passed through the collimator opening.

3. A directional gamma ray detector as set forth in claim 2, wherein the electronic computation system performs coincidence processing to reject Compton interactions in the reaction foil, the first multicell gas chamber, and the second multicell gas chamber.

4. A directional gamma ray detector as set forth in claim 2, wherein the foil is in the shape of a thin plate, the two largest dimensions of the foil and the collimator opening lie in a first plane.

5. A directional gamma ray detector as set forth in claim 4, wherein the collimator includes two collimating plates, each collimating plate being parallel to the first plane and the shield includes at least two shielding plates, each shielding plate lying in the first plane.

6. A directional gamma ray detector as set forth in claim 4, wherein;
- the collimator includes two collimating plates, each collimating plate being parallel to the first plane;
- the shield consists of two shielding plates, each shielding plate lying in the first plane; and the thickness of each of the shielding plates in the direction perpendicular to the first plane is at least six times that of the foil.

7. A directional gamma ray detector as set forth in claim 5, further comprising:
- a drive means, connected to the two collimating plates for varying a distance between the collimator opening and the foil.

8. A directional gamma ray detector as set forth in claim 7, wherein the foil is tantalum.

9. A directional gamma ray detector as set forth in claim 7, wherein the foil is copper.

10. A directional gamma ray detector as set forth in claim 7, wherein the collimator is tantalum.

11. A directional gamma ray detector as set forth in claim 7, wherein the collimator is tungsten.

12. A directional gamma ray detector as set forth in claim 7, wherein:
- the dimensions of the foil are approximately $4\times100\times0.005$ centimeters;
- the dimensions of each collimating plate are approximately $3\times100\times0.15$ centimeters; and
- the shield includes first and second shielding plates having dimensions of approximately $4\times15\times0.15$ centimeters; and
- the shield includes a third shielding plate having dimensions of approximately $4\times100\times0.15$ centimeters.

13. A directional gamma ray detector as set forth in claim 7, wherein the number of gas cells in each multicell chamber is approximately seven hundred fifty and each gas cell is approximately $2\times2\times2$ centimeters.

14. A method of detecting gamma rays originating from a direction of interest, comprising the steps of:
- passing gamma rays originating from a direction of interest through a collimator opening;
- shielding gamma rays originating from directions other than the direction of interest by use of a shield;
- generating an electron and a positron by reacting a gamma ray from a direction of interest with a piece of foil;
- sensing electrons and positrons in three dimensional position sensitive ionization chambers;
- determining the path of the sensed electrons and the path of the sensed positrons; and
- determining whether the path of the sensed electrons and the path of the sensed positrons correspond to a gamma ray which has passed through the collimator opening.

* * * * *

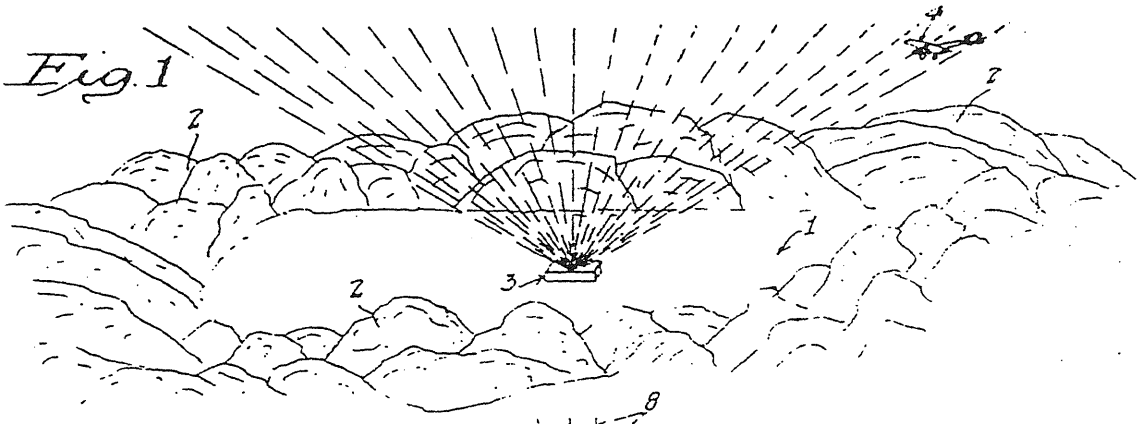
RADIATION COMMUNICATIONS SYSTEMS

Feb. 27, 1934. S. L. WEBER ET AL 1,948,552

RAY AVIATION COMPASS

Filed May 16, 1932 2 Sheets-Sheet 1

Fig. 1



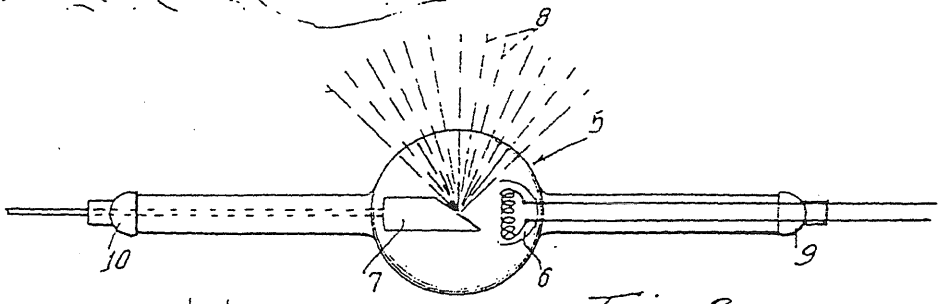


Fig. 2

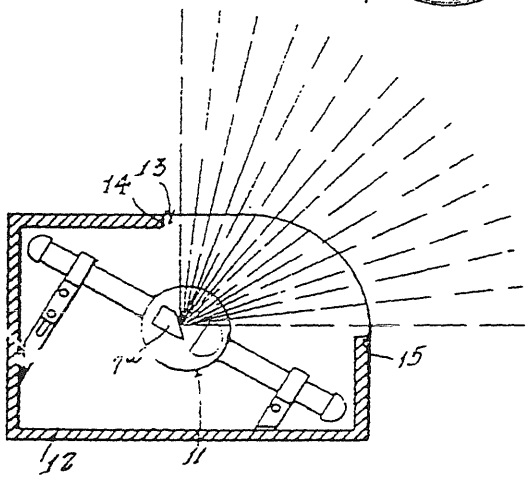


Fig. 3

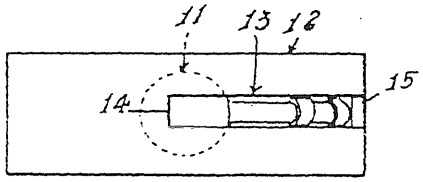


Fig. 4

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RAY AVIATION COMPASS

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Fig. 5

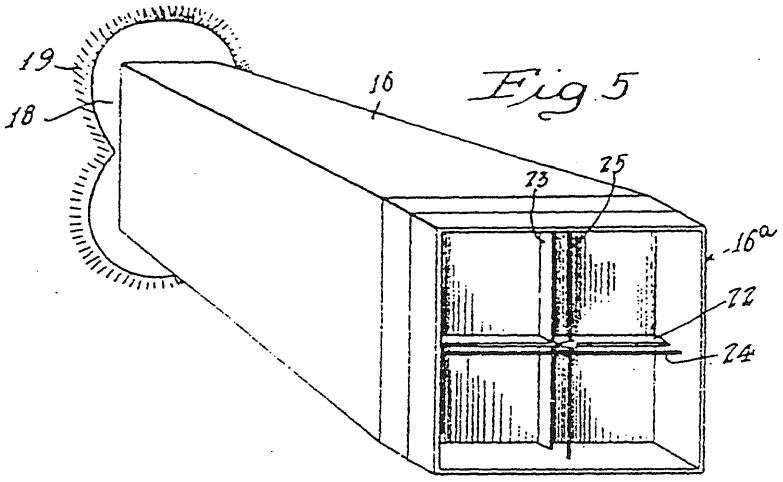


Fig. 6

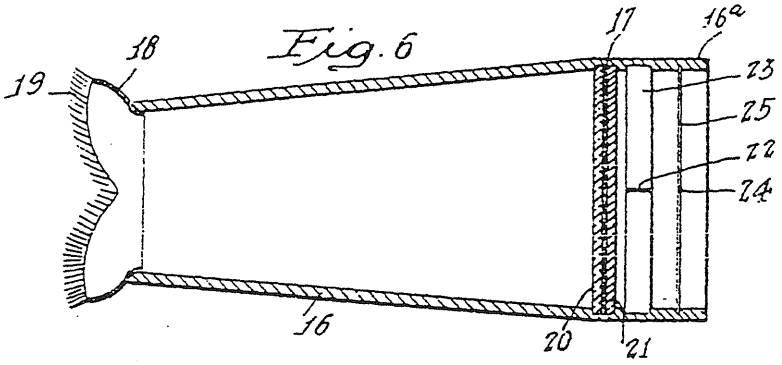


Fig. 7

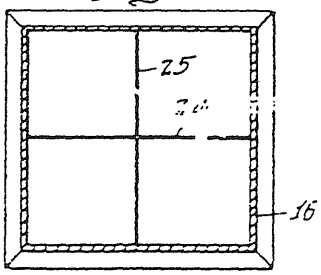


Fig. 8

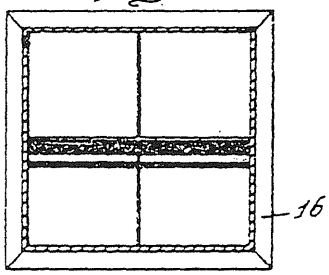


Fig. 9

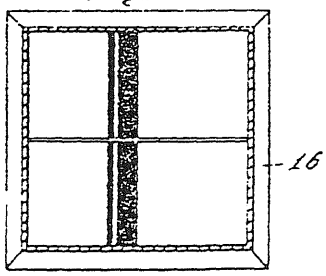


Fig. 10

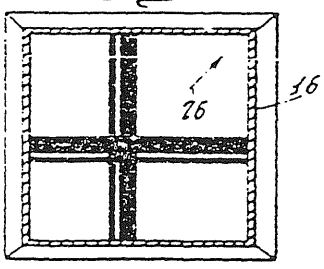
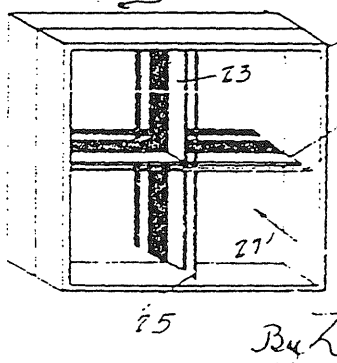


Fig. 11



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Patented Feb. 27, 1934

1,948,552

UNITED STATES PATENT OFFICE

1,948,552

RAY AVIATION COMPASS

Sigvard Leo Weber, Brydon Baker, and Edward W. Jensen, Los Angeles, Calif.

Application May 16, 1932. Serial No. 611,468

7 Claims. (Cl. 250—11)

This invention relates to beacons for aircraft and has as a broad object to provide apparatus for producing an indication on board aircraft of the position of the craft during times when the earth is obscured from view by fog or clouds.

A specific object is to provide a simple receiving device responsive to Roentgen rays for indicating the existence of such rays and the direction of their source.

It is present practice to use beacon lights at intervals along established airways and at landing fields, for guiding airplanes. Such beacons are readily visible in clear weather but are useless in thick weather. Radio beacons have been proposed for use under conditions of poor visibility, but they are open to the objection that relatively complicated receiving equipment is required to indicate the direction of the radio beacon.

In accordance with the present invention we propose to use a source of Roentgen rays as a beacon and determine the position of aircraft relative to the beacon by detecting the presence and direction of the Roentgen rays with a specially designed fluoroscope to be described in detail in the following specification. The chief advantages of the system are that the Roentgen rays are very penetrating, passing readily through fog and clouds, and that the receiving system is simple, cheap, rugged and can be operated by anyone without special training.

Referring to the drawings:

Figure 1 is a perspective view illustrating how a Roentgen ray beacon may be positioned on an aircraft landing field;

Figure 2 is a detail view showing how a conventional Roentgen ray tube may be utilized to produce a diverging beam as shown in Figure 1;

Figure 3 is a detail elevational sectional view of a Roentgen ray tube enclosed in a special housing to confine the radiation to a fan shaped beam;

Figure 4 is a plan view of the apparatus shown in Figure 3;

Figure 5 is a perspective view of a direction indicating fluoroscope in accordance with the invention;

Figure 6 is a longitudinal sectional view of the fluoroscope shown in perspective in Figure 5;

Figures 7, 8, 9, and 10 comprise diagrams illustrating the operation of the fluoroscope; and

Figure 11 is a perspective view of the outer end of the fluoroscope showing the shadows cast by Roentgen rays impinging on the device.

Referring to Figure 1, we have shown a landing field 1, which may be located in the midst of hills 2, equipped with a Roentgen ray beacon 3 for radiating a broad divergent beam of Roentgen rays upward in the form of an inverted cone. An airplane 4 is schematically shown as approaching the field and exposed to the beam of Roentgen rays from the beacon 3. It will be apparent from inspection of Figure 1 that if the airplane 4 is equipped with some device for indicating the direction of propagation of the Roentgen rays emanating from the beacon 3, the aviator will be able to ascertain the direction of the landing field 1 even though the earth below him is entirely obscured from view by fog or clouds.

The particular means for generating Roentgen rays to be used as the source 3 in Figure 1 is not a part of our invention but it may comprise a conventional Roentgen ray tube as shown in Figure 2, which tube comprises a glass envelope 5, a cathode 6 for emitting electrons, and an anode 7 upon the surface of which Roentgen rays are generated and radiated by impact at high velocity of electrons from the cathode 6. The type of tube illustrated in Figure 2 is in common use and it is known that a tube of this sort radiates Roentgen rays in the form of a divergent beam as outlined by the dotted lines 8, the exact direction of radiation being dependent upon the position of the anode 7 and on the angle of impact of the electrons on the anode face. The cathode 6 and anode 7 are connected to terminals 9 and 10 respectively on the exterior of the envelope 5 which terminals may be connected to any source of electrical potential of sufficient intensity to operate the tube. Since apparatus for energizing Roentgen ray tubes is old and well known, such apparatus has not been disclosed in the drawings.

As previously indicated, a Roentgen ray tube of the type shown in Figure 2 produces a cone-shaped beam which would extend horizontally in all directions as shown in Figure 1. Such a beam (as shown in Figure 1) serves the purpose of guiding aircraft to the beacon from any and all points of the compass, and would be particularly useful in connection with landing fields from which airways lead in all directions. A conical beam as shown in Figure 1 will not serve to guide aircraft on a given course as the craft would always be in the Roentgen ray field no matter from what direction it approached the beacon.

In some instances it may be desirable to produce a constricted beam of Roentgen rays limited

to a zone extending along a definite airway. By means of such a beam an aviator can maintain his craft directly on its course at all times by keeping within the beam. Means for producing a beam of this type is disclosed in Figures 3 and 4 which show a Roentgen ray tube 11, similar to that shown in Figure 2, enclosed within a housing 12 of lead or other material substantially impervious to Roentgen rays. The housing 12 is provided with a slit 13 extending from a point 14 substantially vertical with respect to the anode 7a to a point 15 substantially horizontal with respect to the anode. The width of the slit is determined by the width of the beam it is desired to project and may be such as to produce a beam having a divergence horizontally of from 5 degrees or less to fifteen degrees or more. The apparatus disclosed in Figures 3 and 4 would therefore produce a fan-shaped beam having a lateral divergence of only a few degrees and having a vertical divergence of substantially ninety degrees, that is extending from the horizon to the zenith. When such a beam is directed along the line of an airway, aviators equipped with a Roentgen ray detecting device, such as will be described below, will be enabled to ascertain at all times whether they are on or off of their course by noting whether they are within or without the Roentgen ray beam.

To enable aviators to ascertain their position and direction of flight relative to the direction of a source of Roentgen rays, we provide a special fluoroscope as illustrated in Figures 5 and 6. This fluoroscope comprises an elongated case 16 of light-proof material having a fluorescent screen 17 sensitive to Roentgen rays mounted in one end thereof and having a head piece 18 mounted upon the other end. Head piece 18 is dimensioned and shaped to fit about the eyes of an observer and is provided with fur trim 19 about the edges to form a light-tight seal with the head of the observer. The fluorescent screen 17 is preferably of slightly larger dimensions than the head piece 18 and the case 16 is therefore tapered outwardly from the head piece 18 to the fluorescent screen 17, as shown.

As shown in the sectional view of Figure 6 the fluorescent screen 17 is mounted between a plate of lead glass 20 and a piece of cardboard or similar material 21. The lead glass 20 is transparent to light but is opaque to Roentgen rays. It therefore permits the observer to see the fluorescent screen 17 while at the same time blocking the passage of any Roentgen rays that might pass through the screen 17. The cardboard wall 21 serves to protect the fluorescent screen 17 from mechanical injury and at the same time prevent the entry of any light within the case 16. It is essential to provide such a light seal as the fluorescence produced upon the screen 17 by Roentgen rays is relatively feeble and might not be observable if any appreciable amount of light were allowed to leak through to the surface of the screen. The cardboard plate 21 has substantially no impeding effect upon the Roentgen rays.

A fluoroscope as described indicates the presence of Roentgen rays because of the fluorescence of the screen 17 when exposed to the rays. However, it would not indicate with any great degree of accuracy the direction of propagation of the days. For the purpose of indicating the direction of propagation of the rays, a pair of crossed shadow plates 22 and 23 and a pair of crossed shadow bars 24 and 25 are provided in front of the fluorescent screen 17 and spaced slightly therefrom and from each other. The shadow plates and bars may be conveniently supported from the extended walls 16a of the case 16. The shadow plates and shadow bars are constructed of lead or other dense material substantially opaque to Roentgen rays and are of substantially the same lateral dimensions. That is, the thickness of each of the shadow plates 22 and 23 is substantially the same as the diameter of the shadow bars 24 and 25. It therefore follows that Roentgen rays impinging perpendicularly upon the fluorescent screen 17 will produce a single pair of thin crossed shadows on the fluorescent screen, as shown in Figure 7, and an aviator upon seeing thin crossed shadows in the fluoroscope as shown in Figure 7 will know that the instrument is pointed directly toward the Roentgen ray beacon and that by guiding his craft in the direction in which the fluoroscope is pointed he will approach the beacon.

If the fluoroscope, instead of being oriented to directly face the source of Roentgen rays, is directed too low, the vertical plate 23 and the vertical bar 25 will still produce a thin vertical shadow, as shown in Figure 3, but the horizontal plate 22 will produce a relatively broad horizontal shadow and the horizontal bar 24 will produce a second, separate horizontal shadow therebelow. The appearance of these shadows immediately informs the observer that the fluoroscope is directed too low and that by raising it until he gets a single thin horizontal shadow as shown in Figure 7, the instrument will be pointed directly at the Roentgen ray source.

If the fluoroscope is directed at the proper elevation, but to one side of the Roentgen rays source, a thin horizontal shadow will be produced but the vertical plate 23 will produce a broad vertical shadow and the vertical bar 25 will produce a separate, narrow vertical shadow as shown in Figure 9. When such a shadow is obtained, the observer will swing the forward end of the fluoroscope to the right until he obtains a single thin vertical shadow, which will inform him that the instrument is pointed directly toward the source.

If the fluoroscope is misdirected both horizontally and vertically with respect to the source, double horizontal and vertical shadows will be produced as shown in Figure 10. If such a shadow is obtained, the forward end of the instrument should be swung in the direction indicated by the arrow 26 until the double shadows disappear, when the instrument would be properly directed toward the source.

The perspective view of Figure 11 shows clearly how the double shadows will be produced by Roentgen rays impinging obliquely on the fluorescent screen 17 from the lower right hand corner as indicated by the arrow 27.

It will be observed from the foregoing description that we have provided a simple and effective aircraft beacon capable of functioning under all weather conditions, together with a device for detecting the presence and direction of propagation of Roentgen rays on board an aircraft, the detecting device being extremely simple, fool-proof, light in weight, and capable of being operated by any aviator without special training.

We claim:

1. A device for indicating the direction of propagation of Roentgen rays comprising a fluorescent screen rendered luminous by impact of

said rays thereon, means opaque to said rays positioned immediately in front of said screen for producing a shadow thereon, and second means opaque to said rays positioned directly in front of said first means for also producing a shadow on said screen, whereby the shadows produced by said two means overlap when Roentgen rays impinge on said screen at a predetermined angle and are separately visible when said rays impinge on said screen at another, different angle.

2. A device for indicating the direction of propagation of Roentgen rays comprising a fluorescent screen adapted to be rendered luminous by impact of said rays thereon, a shadow-producing element of material opaque to Roentgen rays positioned in front of said screen, said element being of larger dimension in a direction perpendicular to said screen than in a direction parallel to said screen, whereby it projects a narrower shadow on said screen in response to Roentgen rays impinging on said screen perpendicularly than to Roentgen rays impinging on the screen obliquely, and a second shadow producing element similar in shape to said first element but of reduced dimension in a direction perpendicular to said screen and mounted in spaced relation directly in front of said first element, whereby it projects a shadow on said screen coincident with the shadow projected by said first element in response to Roentgen rays impinging on said screen perpendicularly and projects a narrower shadow displaced from the shadow of said first element in response to Roentgen rays impinging on said screen obliquely thereto.

3. In navigation the method of indicating the direction of a reference point on board a moving craft that comprises radiating Roentgen rays from the reference point, intercepting some of said rays on board said craft, and determining the direction of propagation of the intercepted rays.

4. In navigation the method of indicating the direction of a reference point from on board a moving craft that comprises radiating Roentgen rays from the reference point, intercepting some of said rays on board said craft, producing a shadow with the intercepted rays, and producing a direct visible indication of the direction of projection of said shadow.

5. Means for navigating a moving craft comprising, in combination, means for radiating Roentgen rays from a reference point, and means on the craft for intercepting rays radiated from said source and producing a visible indication of their direction of propagation.

6. A device for indicating the direction of propagation of Roentgen rays comprising a fluorescent screen rendered luminous by impact of rays thereon, and means comprising a horizontal and a vertical bar, crossed with respect to each other, and positioned directly in front of said first means, said bars being dimensioned larger in a direction perpendicular to the plane of said screen than in a plane parallel to said screen and being constructed of material substantially opaque to Roentgen rays, whereby they cast shadows upon said screen, the widths of which shadows and the positions of which shadows vary depending upon the angle of incidence of Roentgen rays upon said screen.

7. Means for navigating a moving craft comprising in combination, means for radiating Roentgen rays from a reference point and means on the craft for producing a visible indication of the direction of propagation of the rays, said last means comprising an object opaque to Roentgen rays in combination with means for producing a direct visible indication of the direction of projection of the shadow cast by said object.

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Nov. 19, 1946. W. T. WEBER 2,411,400

SYSTEM FOR DIRECTING THE MOVEMENTS OF AIR AND/OR MARINE CRAFT

Filed July 23, 1943 5 Sheets-Sheet 1

FIG. 1.

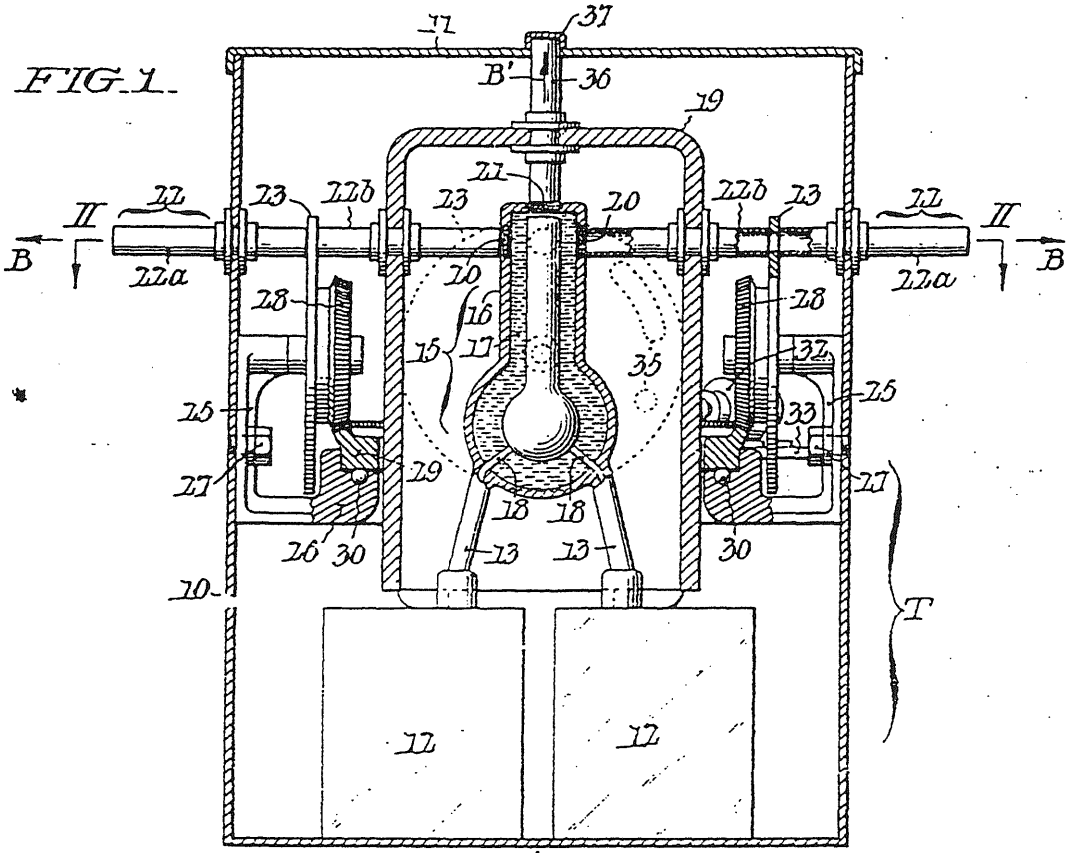
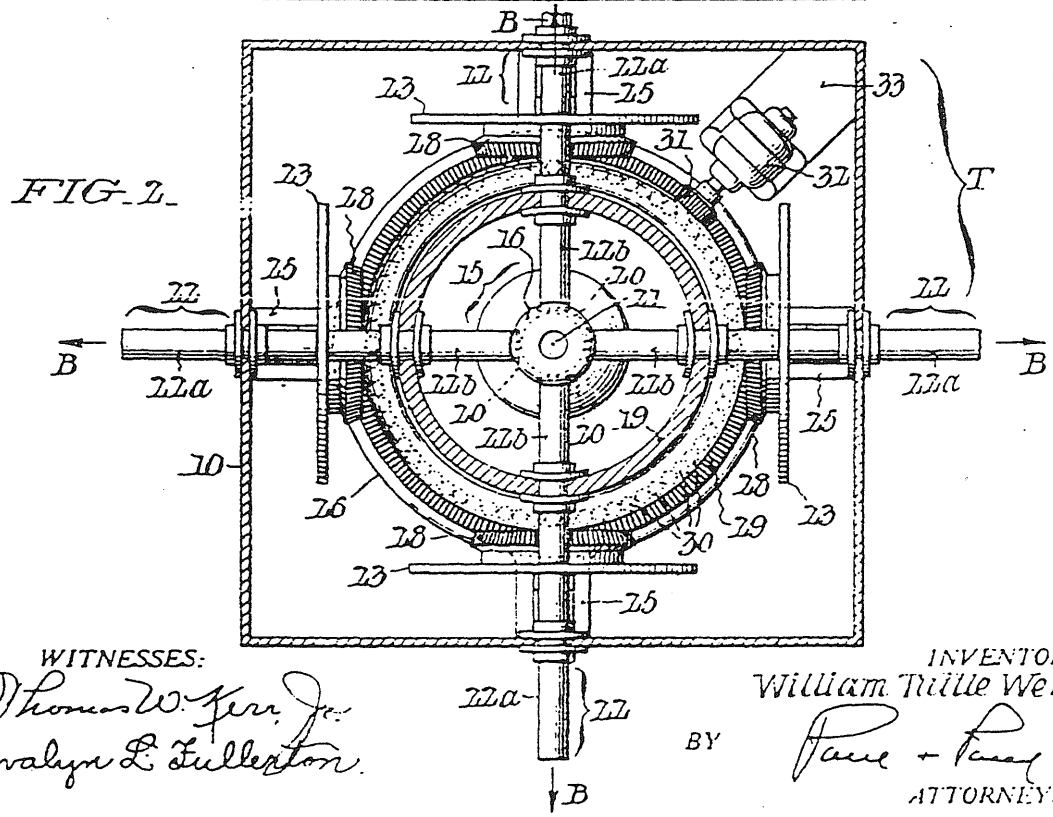


FIG. 2.



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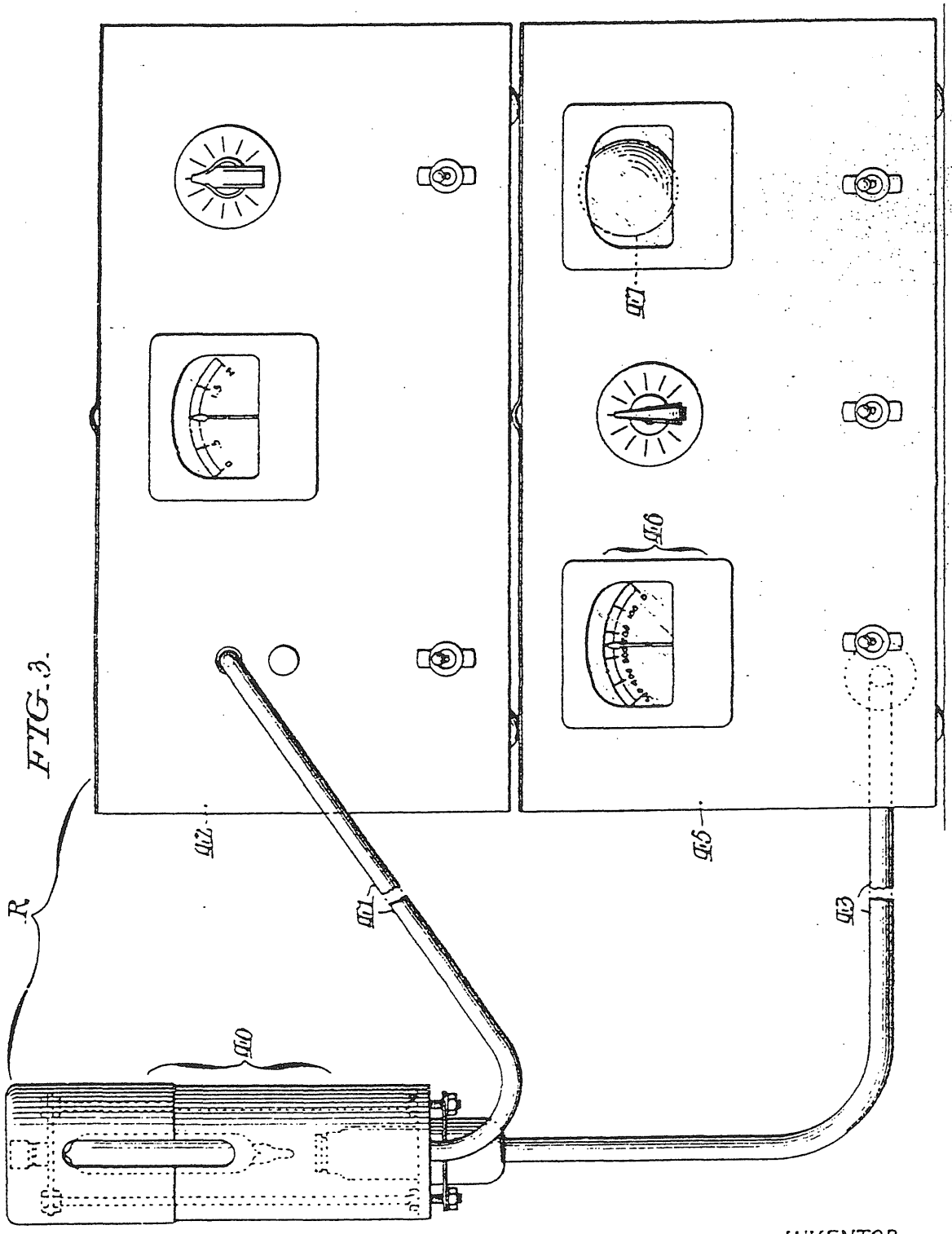
SYSTEM FOR DIRECTING THE MOVEMENTS OF AIR AND/OR MARINE CRAFT

Filed July 23, 1943 5 Sheets-Sheet 2



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SYSTEM FOR DIRECTING THE MOVEMENTS OF AIR AND/OR MARINE CRAFT

Filed July 23, 1943 5 Sheets-Sheet 3

FIG. 4.

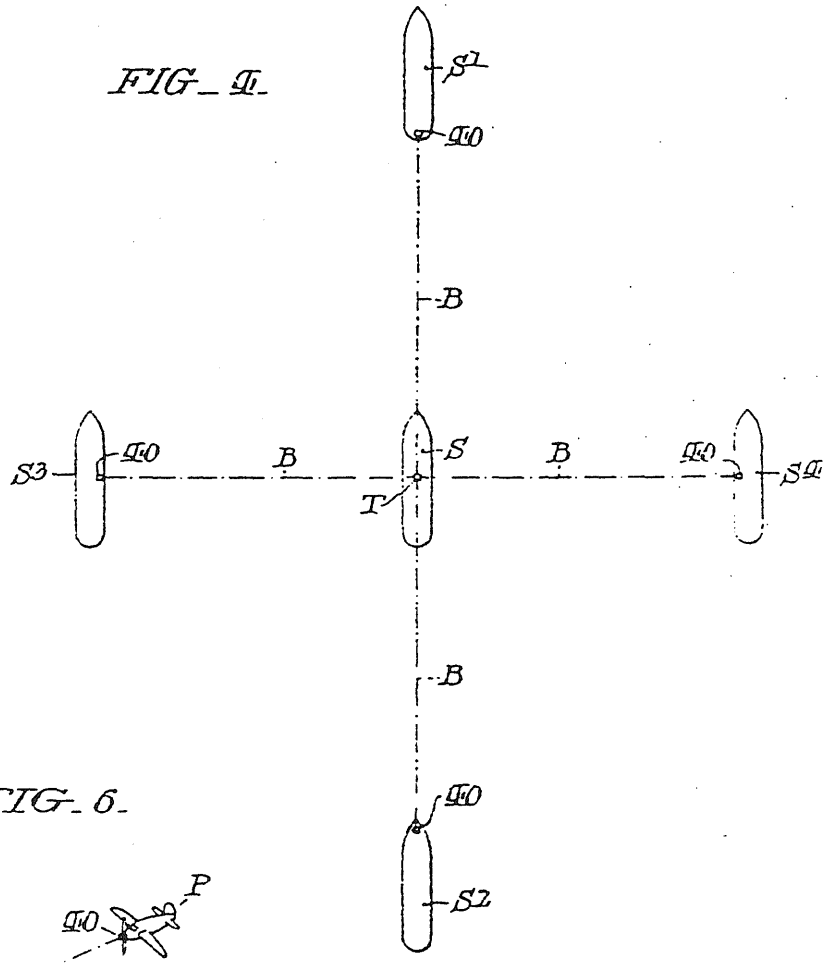


FIG. 6.

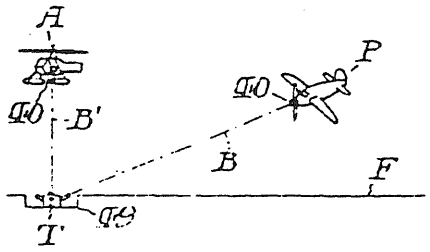
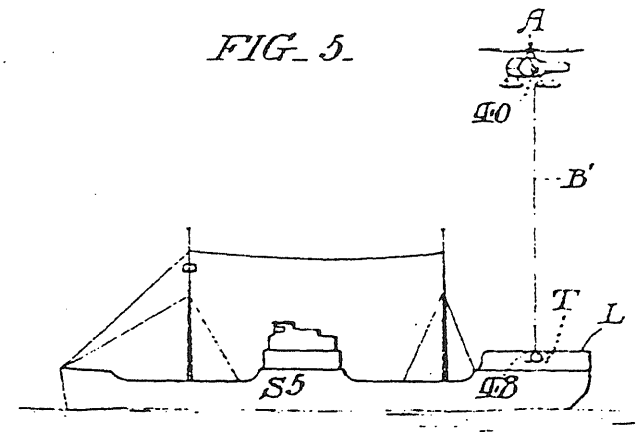


FIG. 5.



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SYSTEM FOR DIRECTING THE MOVEMENTS OF AIR AND/OR MARINE CRAFT

Filed July 23, 1943 5 Sheets-Sheet 4

FIG. 7.

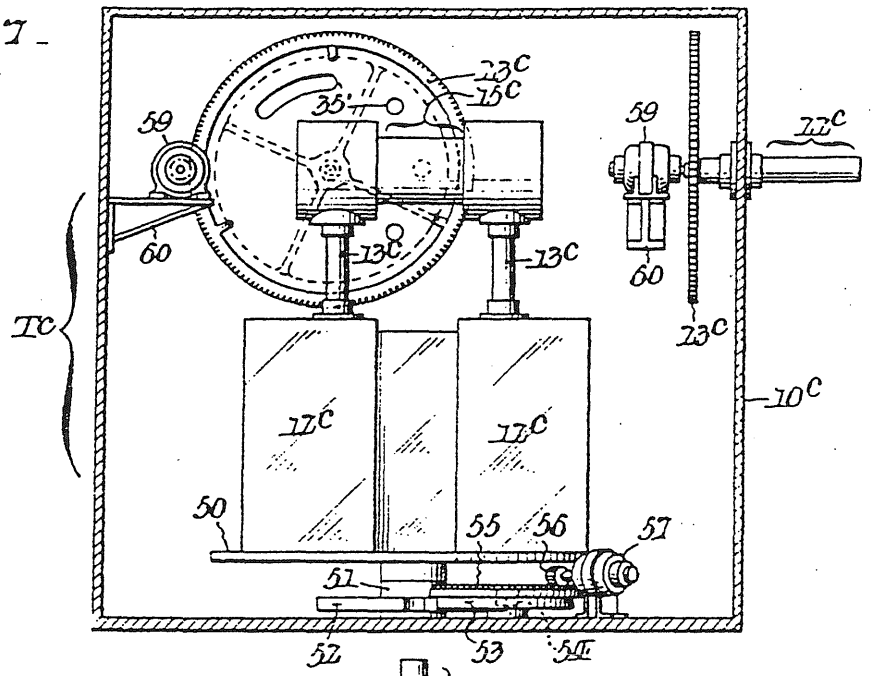
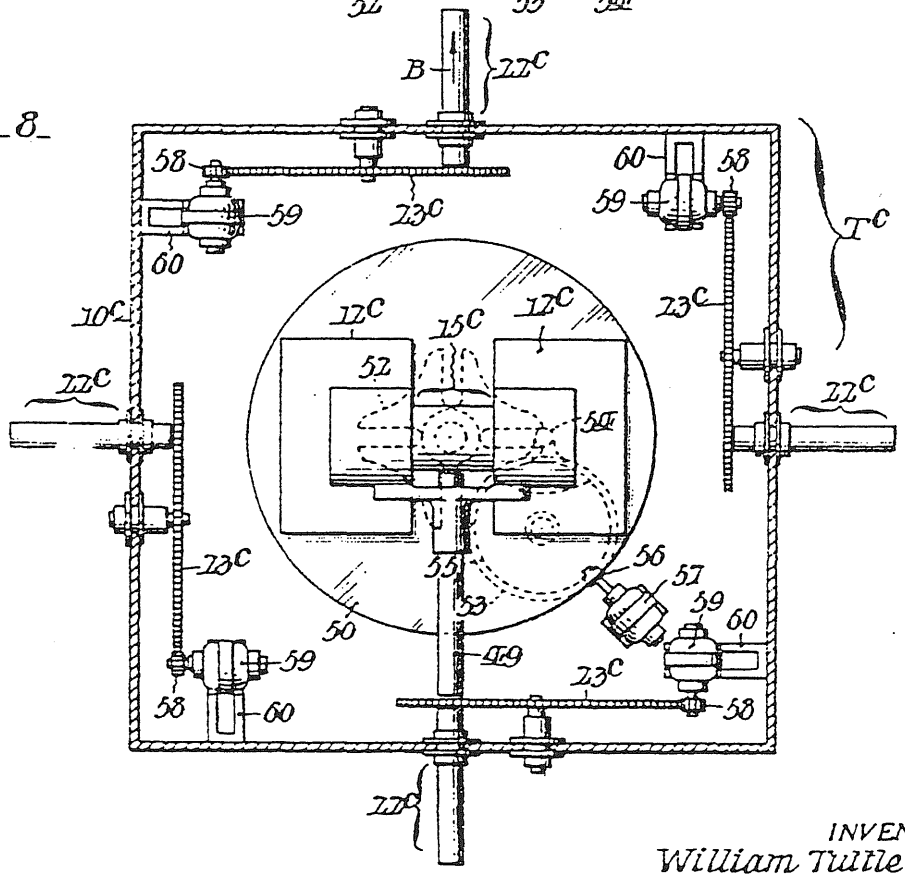


FIG. 8.



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SYSTEM FOR DIRECTING THE MOVEMENTS OF AIR AND/OR MARINE CRAFT

Filed July 23, 1943 5 Sheets-Sheet 5

FIG. 9.

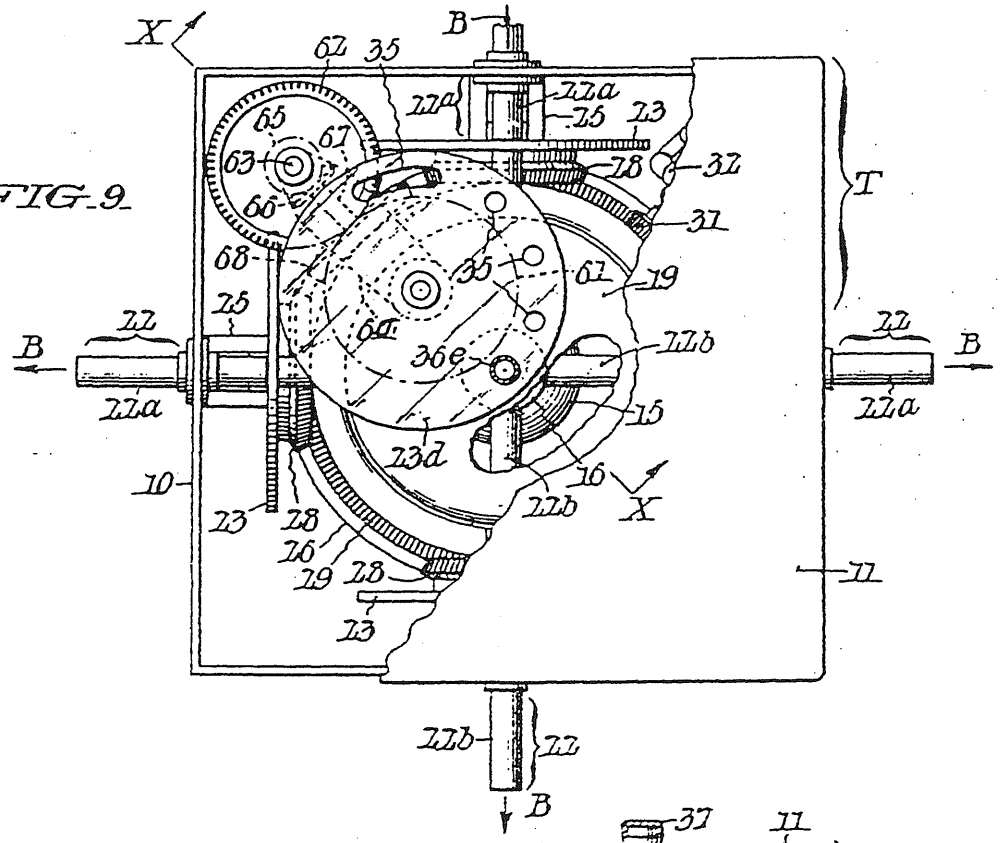
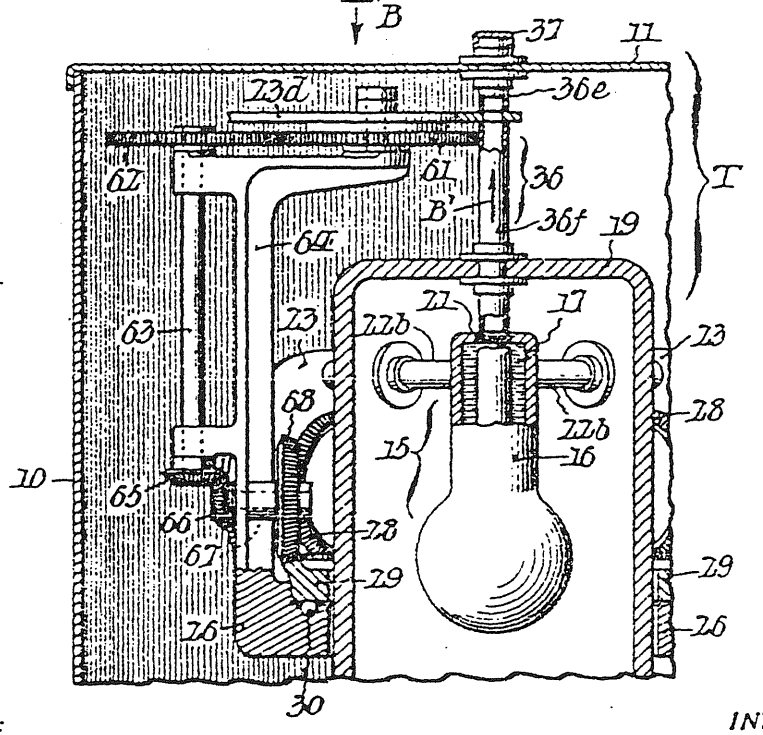


FIG. 10.



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UNITED STATES PATENT OFFICE

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SYSTEM FOR DIRECTING THE MOVEMENTS OF AIR AND/OR MARINE CRAFT

William Tuttle Weber, Lansdowne, Pa., assignor of one-half to Jacob Applebaum, Philadelphia, Pa.

Application July 23, 1943, Serial No. 495,824

16 Claims. (Cl. 250—11)

1

This invention relates to systems useful in directing the courses of ships at sea, particularly ships traveling under convoy in wartime, and for directing aircraft into airports or onto the decks of carriers or other vessels.

I am aware that visible light beacons have been employed heretofore in systems of the kind referred to, but such beacons are not readily seen during the day, nor are they reliable in fog; and moreover by reason of their advantage to the enemy in normal or good weather in disclosing the location of the airports and the ships from which the beams are transmitted.

The aim of my invention is to overcome the above mentioned drawbacks, that is to say, to make possible the guiding of ships and the safe landing of aircraft during the night as well as during the day, regardless of cloud or fog conditions.

This desideratum I attain in practice as hereinafter more fully disclosed through the employment of invisible Roentgen or X-rays, or the like, and through provision of improved means for controlling directional transmission of the rays from airports or ships either as continuous beams, or as periodically intercepted code, producing beams, for reception by suitable detecting devices on the ships or the aircraft which are to be guided.

Other objects and attendant advantages will appear from the following detailed description of the attached drawings, wherein

Fig. 1 is a view in vertical section of a transmitting apparatus conveniently embodying my invention in part and adapted for both marine and land use.

Fig. 2 is a plan section of the apparatus taken as indicated by the angled arrows II—II in Fig. 1.

Fig. 3 is a diagrammatic view of detecting apparatus constructed in accordance with my invention and likewise suitable for both marine and land use.

Fig. 4 is a schematic view showing the manner of operation of my improved system in directing the movement of a group of ships under convoy.

Fig. 5 is a diagrammatic view showing the use of the system in guiding an aircraft to the landing deck of a ship.

Fig. 6 is a view similar to Fig. 5 illustrating the use of the system in guiding aircraft to a landing field of an airport.

Figs. 7 and 8 are views corresponding to Figs. 1 and 2 showing an alternative form of transmitting apparatus.

Fig. 9 is a view also like Fig. 2 illustrating a modification of the transmitting apparatus; and

Fig. 10 is a fragmentary sectional view taken as indicated by the angled arrows X—X in Fig. 9.

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With more detailed reference first more especially to Figs. 1 and 2 of these illustrations, the transmitting apparatus there delineated and generally designated by the letter T has a box-like housing 10 which is preferably of iron with a lining or coating of lead, and which is provided with a removable lid 11 of like material so that when necessary access may be had to the parts about to be described at its interior. Suitably fixed in position in the lower portion of the housing 10 is a pair of transformers 12; and supported atop these transformers in the vertical axis of the housing by struts 13, is a Roentgen or X-ray generator 15 of which the bulb is surrounded by a sheathing 16 of lead with provision of a jacket 17 for circulation thereabout of oil or other cooling fluid. The generator 15 is more or less diagrammatically exemplified as being one of a new, recently developed type capable of emitting its rays in all directions, said tube being supplied with current at high voltage through leads 18 extending down through the struts 13 for connection in circuit with the transformers 12 in a well known manner. The generator 15, as a whole, is disposed within a shielding shell 19 having walls of relatively thick lead, said shell resting on top of the transformers 12 and being open at the bottom as best seen in Fig. 1. In adapting the generator 15 to the purposes of my invention, I form the upper cylindric portion of its sheathing 16 with a plurality of windows 20. In the illustrated instance there are four of such windows 20 circumferentially spaced at a quadrant and facing the four walls of the housing 10. There is also provided, for a purpose later on explained, a similar window 21 axially of the top of the sheathing 16. Aligned with the lateral windows 20 of the sheathing 16 are beam emission tubes 22 each such tube being formed in two coaxially-arranged sections 22a, 22b which are suitably secured in the side walls respectively of the housing 10 and the shell 19, and which are separated by an interval for projection therebetween of the edge portion of a disk 23. The four disks 23 are supported for rotation about horizontal axes by radial arms 25 of an annular frame 26 which is secured by screw bolts 27 whereof the threaded shanks pass through apertures in said arms and take into the side walls of the housing 10. Affixed to each disk 23 is a bevel gear 28 in mesh with a bevel gear ring 29 which revolves in a recess in the annulus 26 and which is supported on bearing

balls 30. In the use of the apparatus, the bevel gear ring 29 is constantly driven by an intermeshing bevel pinion 31 on the shaft of an electric motor 32 mounted on a bracket 33 in one corner of the housing 10. As instanced in dotted lines in Fig. 1, each disk 23 is formed with a series of perforations 35 adapted as the disk revolves to pass the corresponding window 20 in the sheathing 16 of the X-ray bulb. The apertures 35 may be in the form of circular holes or elongate slots, or combinations of the two to produce periodic flashes of the beam B for the purposes of code signaling. The perforations of the disks 23 may be identical throughout or they may differ, depending on the character of the code messages which are to be transmitted. Aligned with the upper window 21 in the sheathing 16 of the X-ray bulb is a tube 36 which is fixed in the top wall of the shell 19 and which passes out through an opening in the lid 11 of the casing 10, being itself provided with a removable cover 37 which is of course removed when the vertical beam B' is to be used.

For detection of the X-ray beams or code signals transmitted from the apparatus T of Figs. 1 and 2, I have devised the receiving apparatus pictured in Fig. 3 and generally designated by the letter R. As shown, this receiving apparatus includes a bulb device generally indicated by the numeral 40 which is sensitive to X-rays and which is commercially known as a "Geiger" counter. The power input cable 41 of the device 40 is connected to a power pack which may be of any approved commercial type and which is herein represented by its casing 42. The output cable 43 of the device 40 is, on the other hand, connected to an electronic amplifier, which, like the power pack, may be of any approved type, said amplifier being herein likewise represented by its casing 45. In accordance with my invention, the dial of the milli-ammeter 46 of the amplifier (which meter, let it be understood, is of the damped or ballistic type capable of registering continuously) is calibrated to indicate distances in feet rather than current strength as ordinarily. The amplifier is moreover shown as having a light bulb 47 for visibly indicating the signals received, and, if desired, an electric bell or other audible signal means may be connected in circuit with the light bulb for synchronous operation therewith.

When employed to transmit signal beams to control the movements of a group of convoyed ships the transmitting apparatus T is mounted as shown in Fig. 4, at a suitable point on a master ship S, amongst a group of convoyed ships S', S2, S3 and S4, so that the beams B are flashed forward and rearward and sidewise to said convoyed ships as indicated by the dot-and-dash lines. The transmitter may be located at any convenient location on the ship S. Each of the ships S'—S4 is provided at a convenient location with a receiver 40 for detection of the beam or code messages transmitted from the master ship S. The receiver 40 may be mounted with capacity for being turned about its vertical axis, about half way up a mast of each of the convoyed ships with the slot of its bulb device facing the master ship S and the other parts of the receiving apparatus located on the bridge or in a cabin set apart for them as may be found convenient or desirable. With the aid of the meter 46 of the receiving apparatus, it will be seen that each convoyed ship can be maintained at a definite distance from the master ship not only during the day but at night and in spite of cloudy or foggy weather conditions. By turning the receiver 40 it will be possible to find the beam intended for it if the convoyed ship should stray from the desired course in a manner which will be readily understood from Fig. 4.

Fig. 5 illustrates how the vertical beam from the transmitter T of my invention is utilized to direct an autogyro A to a landing deck L of a ship S5. In this case the transmitter is recessed into the deck L as at 48, and the receiver 40 located at the bottom of the fuselage of the autogyro.

In Fig. 6 the system is shown arranged for directing ordinary planes and autogyros to a landing field of an airport. Here the transmitting apparatus T is recessed at 49 into the surface F of the airport, said apparatus being like that illustrated in detail in Figs. 1 and 2 except for having its tubes 22 arranged to angularly direct the beams B for guidance of ordinary plane P, while its vertical beam B' is used for directing the autogyro A. In the case of the ordinary plane P the receiver 40 may be placed in the noses of the fuselages, and in the case of autogyros in the bottoms of the fuselages as indicated.

In the alternative form of transmitting apparatus T' illustrated in Figs. 7 and 8, a Roentgen tube 15c is of the ordinary type which transmits its rays only in the direction indicated by the arrow in Fig. 8. In this instance the transformers 12c and the tube 15c are supported upon a turntable 50 which is suitably journaled for rotation in a bearing 51 at the bottom of the housing 10c, and which is arranged to be intermittently rotated through a quadrant at each actuation by a "Geneva" movement whereof the star wheel is designated 52 and the cooperative disk 53 which carries the drive pin 54. Connected to the disk 53 is a bevel gear 55 (see Fig. 7) which is in turn driven by a bevel gear pinion 56 on an electric motor 57 fixedly supported within the housing 10c. Incident to the dwells between the intermittent rotary shifts of the table 50, the rays emitted from the generator are directed into a confining tube 49 supported on said table and successively through the tubes 22c, which, as in the first described embodiment, are suitably secured in the side walls of the housing 10c, the rays being intercepted in each instance by a perforated disk 23c in the same manner as described in connection with the first embodiment. Here, however, the disks 23c are formed with peripheral teeth which mate with drive pinions 58 on the shafts of individual electric motors 59 supported by brackets 60 from the walls of the housing 10c.

The modified transmitter illustrated in Figs. 9 and 10 is identical with that shown in Figs. 1 and 2 except that here a separate coding disk 23d is provided to periodically intercept the vertically directed beam. The disk 23d is rotated through the medium of auxiliary drive means which includes a pair of intermeshing spur gears 61 and 62 whereof the first is affixed to said disk and the other to the upper end of a vertical shaft 63. As shown, the shaft 63 is journaled in an upward bracket extension 64 of the annulus 26 at one corner of the housing 10, which bracket also rotatively supports the disk 23d. To the lower end of the shaft 63 is secured a miter pinion 65 that mates with a similar miter pinion 66 on the outer end of a short horizontal shaft 67 also journaled in the bracket extension 64 and provided at its inner end with a bevel gear 68 that meshes with the gear ring 29. The proportion-

ing of the gears 61, 62, 65, 66 and 68 in the illustrated instance is such that the disk 23d is rotated at the same speed as the disks 23. However, if found to be desirable it may be otherwise proportioned for rotation of the disk 23d at a differential speed. As further shown, the edge portion of the disk 23d extends into an interval in the directing tube 36d which, like the tubes 22, is made in two sections 36e and 36f.

Having thus described my invention, I claim:

1. In a system of the character described, a transmitter for emitting a directional X-ray beam from a ship or a landing port; an X-ray detector for carriage on another ship or on an air craft to be guided; and means influenced by the output from said detector to directly indicate the distance of the latter from said transmitter.

2. The invention according to claim 1, further including means embodied in the transmitter for periodically intercepting the beam to produce code signals; and means associated with the detector for visibly indicating the code signals.

3. The invention according to claim 1, further including means embodied in the transmitter for periodically intercepting the beam to produce code signals; and means associated with the detector for visibly and audibly indicating the code signals.

4. In a system of the character described for directing the course of ships in convoy, a transmitter carried by a master ship amid the convoy group and adapted to emit directional X-ray beams laterally in several different directions; and X-ray detectors carried respectively by the other ships in the group, each such detector having associated with it means for directly indicating the distance between the corresponding ship and said master ship.

5. The invention according to claim 4, wherein the transmitter on the master ship embodies means for periodically intercepting the beams to produce code signals; and wherein the detector on each of the other ships embodies means for visibly indicating the code signals received.

6. The invention according to claim 4, wherein the transmitter on the master ship embodies means for periodically intercepting the beams to produce code signals; and wherein the detector on each of the other ships embodies means for visibly and audibly indicating the code signals received.

7. The invention according to claim 4, wherein the transmitter also emits a directional beam vertically for guidance of aircraft to a landing deck on the master ship.

8. A transmitter for a system of the character described including a bulb capable of emitting X-rays in all directions, a sourrounding casing with a plurality of circumferentially-arranged windows, and means confining the beams emanating from said windows for directional projection.

9. A transmitter according to claim 8, including means for periodically intercepting the projected beams to produce code signals.

10. A transmitter according to claim 8, wherein the confining means are in the form of radial tubes respectively in line with the windows.

11. A transmitter according to claim 8, wherein the confining means are in the form of radial tubes respectively in line with the windows; and further including perforated screening means to pass through interruptions in the tubes and thereby periodically intercept the beams for the purpose of producing code signals.

12. A transmitter according to claim 8, wherein the confining means are in the form of radial tubes respectively in line with the windows; further including rotary disks with perforated edge portions projecting into interruptions in the respective tubes; and means for rotating the disks to cause periodic interception of the beams for the purpose of producing code signals.

13. A transmitter according to claim 8, wherein the confining means are in the form of radial tubes respectively in line with the windows; further including rotary disks with perforated edge portions projecting into interruptions in the respective tubes; and means for rotating the disks to cause periodic interception of the beams for the purpose of producing code signals, the last mentioned means comprising gear wheels in individual fixed relation to the disks, an intermeshing master gear wheel, and a motor for driving the master gear wheel.

14. A transmitter according to claim 8, wherein the casing for the bulb is provided with a window at the top; and means for confining the additional beam emanating from the last mentioned window for vertical projection.

15. A transmitter for a system of the character described including a bulb which emits an X-ray beam laterally; a surrounding protective housing with means at intervals perimetrically thereof to confine the beam for directional projection; and means for intermittently rotating the bulb through partial turns to vary its beam into line successively with the individual confining means.

16. A transmitter according to claim 15, further including means for periodically intercepting the beam at each dwell in the rotation of the bulb for the purpose of producing code signals.

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Dec. 3, 1946. E. McDERMOTT 2,412,165

SUBMARINE DETECTING METHOD AND APPARATUS

Filed March 7, 1942 2 Sheets-Sheet 1

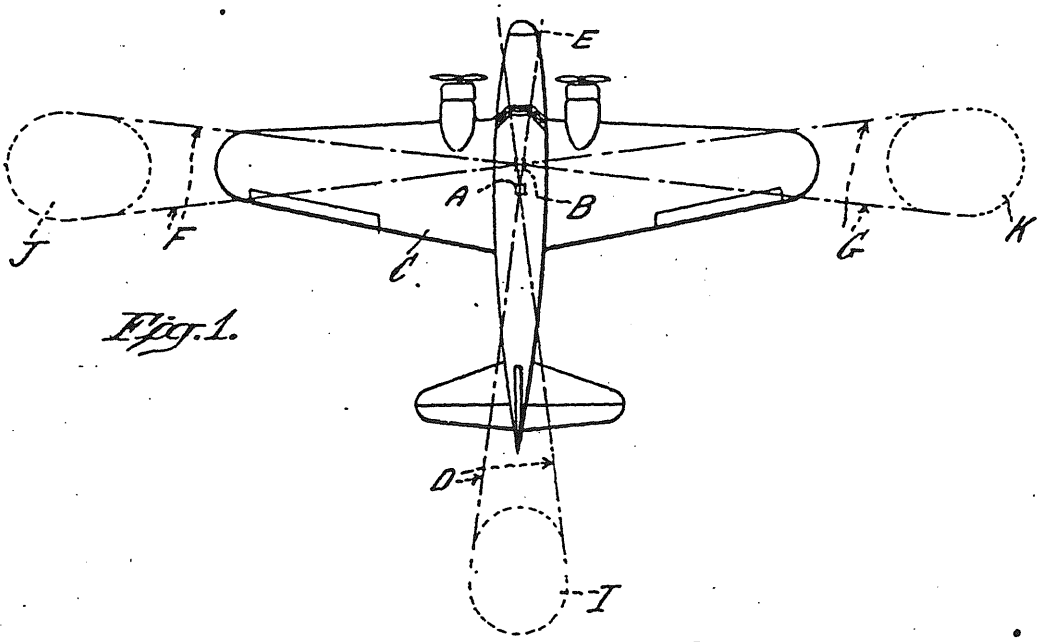

Fig. 1.

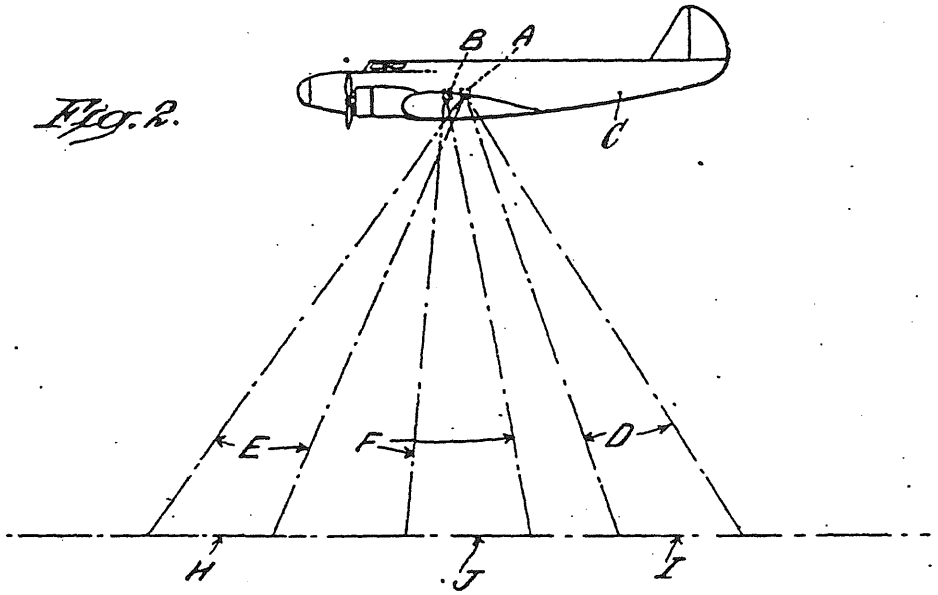

Fig. 2.

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SUBMARINE DETECTING METHOD AND APPARATUS

Filed March 7, 1942 2 Sheets-Sheet 2

Fig. 4.

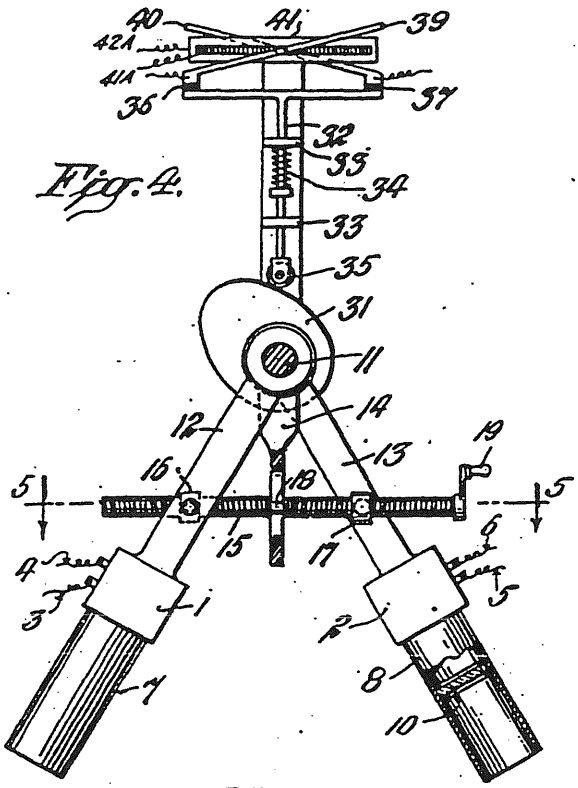


Fig. 3.

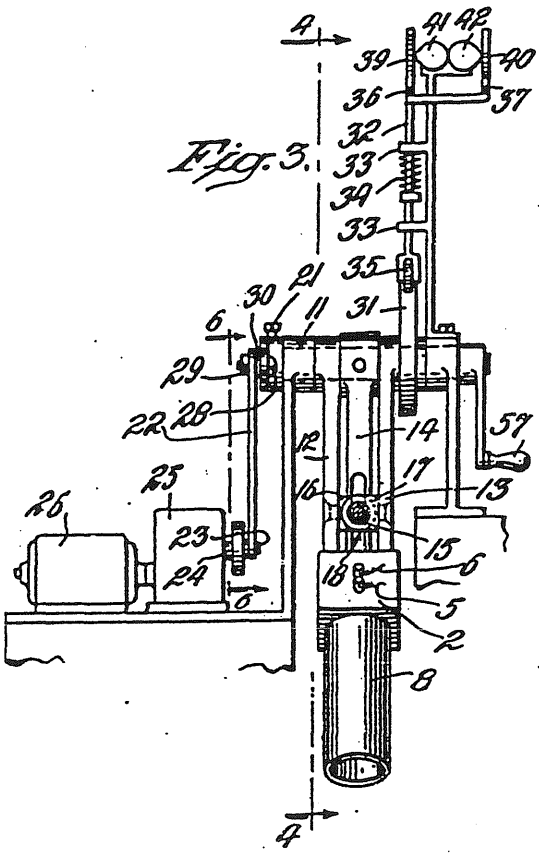


Fig. 5.

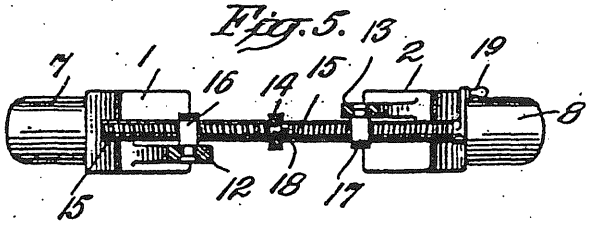


Fig. 6.

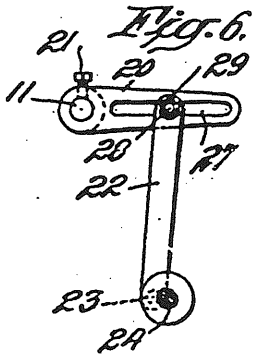
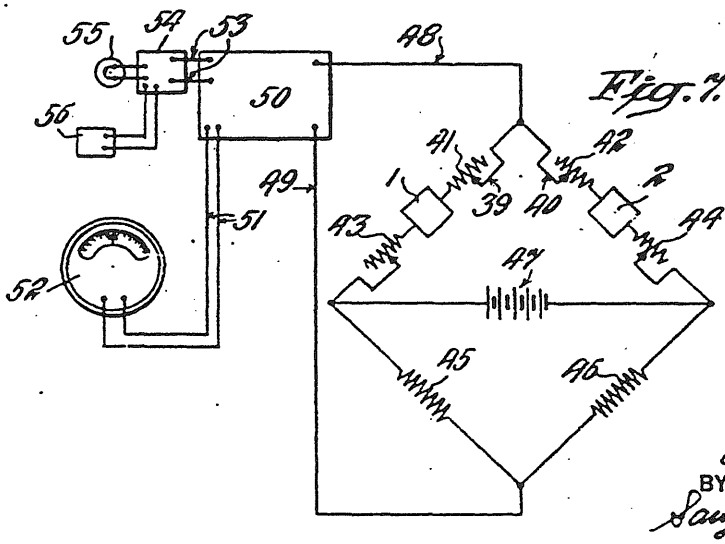


Fig. 7.



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2,412,165

SUBMARINE DETECTING METHOD AND APPARATUS

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Application March 7, 1942, Serial No. 433,836

4 Claims. (Cl. 250—83.3)

1

This invention relates to heat detecting methods and apparatus, and more particularly to a method and mechanism for detecting relatively warm surface areas or objects from aircraft.

It is an object of the invention to provide a method of detecting the presence of ships, and more particularly submarines, by detecting the slightly heated wake created by such vessels.

A further object of the invention is to provide an improved method and apparatus for detecting such heated areas, or other heated areas, from aircraft.

With these objects, and still others which will appear in the course of the following full description in mind, the invention consists in the novel methods, combinations and arrangements of parts and details of construction which will now first be fully described in connection with the accompanying drawings and then pointed out more particularly in the appended claims.

In the drawings:

Figs. 1 and 2 are, respectively, a schematic plan view and side elevation of an airplane, indicating the scanning method employed in detecting heated water areas;

Fig. 3 is a side elevation of a heat detecting device embodying the invention in a preferred form;

Fig. 4 is a vertical section taken on the line 4—4 of Fig. 3;

Fig. 5 is a horizontal section taken on the line 5—5 of Fig. 4.

Fig. 6 is a vertical section taken on the line 6—6 of Fig. 3; and

Fig. 7 is a schematic view and circuit diagram of indicating apparatus used in conjunction with the device of Figs. 3 to 6.

Referring now to Figs. 1 and 2, the invention contemplates the use of thermoresponsive devices A and B, mounted in an aircraft C, in any convenient location, and adapted to register heat conditions of a surface below. Device A will preferably scan or register heat conditions in so much of an area as falls within the rearward and forward conical fields of view D and E, while device B will scan areas falling within similar lateral fields of view F and G.

The thermoresponsive devices A and B are fairly directional. That is to say, no attempt is made to bring an object to focus upon a thermosensitive element and in this way to measure or attempt to measure its temperature, as has been done or attempted in certain prior proposals. According to the present invention, thermosensitive elements are used to indicate the

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presence of comparatively large areas having a temperature different from surrounding areas. Typical of such areas is the "heat track," as it may be called, which is necessarily left in the wake of any vessel and particularly of a submarine when submerged. While the temperature difference is necessarily small, the area falling within the "field of view" of the thermosensitive devices may be made relatively quite large, of the order of a hundred feet in diameter, thus furnishing a reliable indication of heat differences.

In practice, an airplane C will patrol a given area of water, the thermoresponsive devices A and B being rocked or oscillated fore and aft and laterally, respectively, so as to sweep or scan the complete area being patrolled. Oscillation of device A, combined with the motion of the airplane, results in the scanning of an area or strip producing wide coverage without sacrifice of sensitivity. The elements registering the temperature conditions within fields of view E and D will preferably be differentially connected so that a difference in temperature of the water between the areas H and I will be indicated, while constant temperature conditions as between these two areas will not affect the readings. Similarly, the elements which register the temperature conditions within the fields F and G, or the surface areas J and K, will be differentially connected so that they remain unaffected except by changes in the relative temperatures of these areas. The areas scanned, as devices A and B are oscillated, will necessarily vary and accordingly the oscillation of the devices A and B will in itself tend to produce changes in the readings or indications obtained. This factor may be cancelled out in various ways as, for example, by automatically varying the width of the field of view as the device A or B oscillates. An electrical mechanism for accomplishing this result is described below. A more specific description of various features of the method of detecting heated areas will be found in the following description of a suitable mechanism for use in practicing the method of the invention.

Referring now to Figs. 3 to 6, there is illustrated in diagrammatic form a mechanism which is suitable for use as either one of the heat responsive devices A or B referred to. Such a device includes a pair of heat sensitive elements such as thermocouples or bolometers 1 and 2 provided with connecting leads 3, 4, 5 and 6, and fitted with suitable optical apparatus including hoods 7 and 8 for shutting out stray or undesired radiations and lens and filter elements 10 as indicated

diagrammatically in the broken away portion of hood 8. Filter elements are preferably employed which will cut out the entire visible and higher range of the spectrum, or substantially the entire visible range, permitting only the infra-red or heat rays to affect the thermocouples or other thermosensitive elements. The elements 1 and 2 are mounted swingingly about a shaft 11 by means of arms 12 and 13 and are held in fixed position relative to the shaft by means of a centrally located member 14 to which they are connected by means of a right and left threaded screw 15, which passes through nuts 16 and 17 pivotally mounted on the respective arms 12 and 13 and also through a bushing or bearing 18 upon the member 14. Screw 15 is provided with a handle 19, by turning which the angle between arms 12 and 13 may be varied while keeping them at all times symmetrical about the central member 14. The shaft 11 is oscillated by means of a crank arm 20, fastened thereto by a set screw 21, and connected by a rod 22 to crank pin 23 which in turn is rotated by a shaft 24. Shaft 24, through reduction gear box 25, is driven by an electric motor 26. Variation in the extent of oscillation of shaft 11 is provided for by means of slot 27 in arm 20 and bolt 28 passing therethrough and fixable at any position therealong by means of nut 29, the latter being provided with the usual neck 30 passing through rod 22 and serving as a pivotal bearing for the rod 22.

Means is provided for compensating for the variation in area viewed during oscillation, referred to above, and includes a cam 31 fixed to the shaft 11 and a cam rod 32 slidably mounted in brackets 33 and urged downwardly by a spring 34 so as to press roller 35 at its lower end against the surface of cam 31. Mounted at the upper end of rod 32 and electrically insulated therefrom, as by means of insulating blocks 36 and 37, are a pair of rheostat control arms 39 and 40 operating on the rheostat resistance elements 41 and 42. The rheostat elements are connected so that an upward movement of the cam rod 32 decreases the resistance of the one rheostat and increases that of the other, whereas a downward movement has the opposite effect. The connections for the resistance elements 41 and 42 are respectively indicated by the reference numerals 41A and 42A. Referring now to the circuit diagram of Fig. 7, showing a differential connection for the thermosensitive elements 1 and 2, these elements are connected in series with the rheostats 39, 41 and 40, 42, previously referred to, in respective sides of a bridge circuit including also trimming rheostats 43 and 44 as shown. As will be understood, the trimming rheostats are necessary merely for compensation for different circuit characteristics of the elements. The bridge circuit includes resistors 45 and 46 in its opposite arms, the usual source of current 47, and leads 48 and 49 in the control circuit, which terminate in an amplifier 50. As will be understood, the bridge circuit shown is suitable for use with thermosensitive elements of resistance-variation type, and is merely illustrative. Any suitable one of the conventional differential circuits may be employed the specific differential circuit, old in itself, forming no part of the present invention.

Amplifier 50 is provided with outputs connected through conductors 51 to an electrical meter of the ordinary dial type, 52, and also through conductors 53 to a relay 54 which is adapted to operate a light signal 55 and bell 56. Here again, the specific type of amplifier 50 and meter 52 employed form no part of the present invention. One suitable combination is the well known vacuum tube voltmeter direct current amplifying arrangement, with its characteristic stability and linearity of calibration.

The various elements referred to will preferably be arranged so as to center the pointer of the meter 52 when the electrical conditions of the bridge are balanced so that it swings to either side, depending upon which of thermosensitive devices 1 and 2 has the lower resistance. As will be understood, the elements are similarly arranged so that relay 54 will operate the visual signal and bell upon any condition of unbalance exceeding a threshold which is set so as to avoid indication of minor transient temperature variations.

Cam 31 is arranged so that the extreme limits of oscillation of shaft 11 will bring its high point and low point respectively under the roller 35, this roller being in mid position when the arms 12 and 13 are symmetrical about the vertical. The curve of the surface of cam 31 is arranged with relation to the characteristics of rheostats 41 and 42 so that an automatic compensation for the effect of varying field of view of the thermocouples 1 and 2, due to oscillation of shaft 11, is obtained. Such compensation will vary with service conditions and particularly with the height of an airplane over the water surface and may readily be provided for by utilizing interchangeable cams having suitably shaped surfaces.

Considering now, for example, the device of Fig. 4 to be mounted in an airplane with the shaft 11 running crosswise so that the oscillation is fore and aft, no unbalance will be created in the bridge circuit sufficient to operate the light and bell signals so long as the temperature conditions of the water below are normal. As soon, however, as the field of view of thermocouple 1 or 2 crosses the slightly warm wake or "heat track" of a vessel such as a submerged submarine, a condition of unbalance will be created, causing the signals 55 and 56 to operate and permitting the determination of its direction and intensity by means of meter 52. At the same time, the similar device B mounted with its shaft 11 running fore and aft and fields of view oscillating from side to side, will furnish a further indication. These two indications may be used to estimate with considerable accuracy the position of the heat track causing them and a more precise location may be computed by scanning the approximate location at a lower altitude or speed, or both. Particularly for the latter purpose, a slow, manual oscillation may be desirable, and accordingly the devices are provided with means such as handles 57 (Fig. 3) keyed to the shafts 11 to permit oscillation by hand instead of through the electric motors 26.

As will be apparent, devices A and B, each of which employs only a single thermocouple or other heat sensitive device may be used, but in this event the same sensitivity and freedom from the effects of insignificant transient local temperature changes cannot be expected. It is also possible, in some cases, to employ fixed thermoresponsive devices, utilizing the motion of the aircraft to obtain a scanning effect. Further a single device A or B may be employed, but again with a sacrifice of the full benefit of the invention. As will also be apparent, the device and method of the invention may be utilized for locating relatively large land areas or objects such as factories, where there is a significant tem-

perature difference between the same and the surrounding terrain and may, in fact, be utilized for the direction of bombs or depth charges under conditions where visual sighting is impossible. It may also be used for locating coast lines.

An important advantage of the present invention over previous proposals arises from the employment of heat responsive and fairly directional detector elements differentially connected, resulting in comparative freedom from disturbance by reflected radiations. Such disturbance by reflected radiations may of course result from differing reflective power of various water areas, due to waves or ripples caused by wind, or may be caused by variation due to changes in incident sunlight caused by cloud shadows or the like. In this connection, it will also be recalled that heat radiations, being of greater wave length, are much less subject to variation in intensity due to atmospheric conditions than are the shorter radiations of the visible spectrum. By differentially connecting the detector elements changes in atmospheric conditions, such as temperature changes, do not affect the operation of the device.

What is claimed is:

1. The method of locating a submarine from aircraft which comprises traversing an area to be patrolled and scanning the surface thereof with fairly directional heat detectors, substantially insensitive to light waves within the visible and higher portions of the spectrum, one of the said detectors being oscillated fore and aft and another of the said detectors being oscillated laterally to scan two strips of said surface, and locating thereby the heat track of a submarine.

2. A heat detector for locating surface objects and areas from aircraft comprising in combination two fairly directional thermosensitive elements disposed at an angle to scan separate areas, means for oscillating said elements as a unit, and a differential indicator circuit for registering relative variations in temperature between the areas scanned by the said elements.

3. A heat detector according to claim 2, comprising also compensating means for eliminating variations upon said thermosensitive elements due to oscillation thereof by said oscillating means.

4. A heat detector according to claim 2, comprising also compensating means for eliminating variations upon said thermosensitive elements due to oscillation thereof by said oscillating means, said compensating means including variable resistance elements in said differential circuit and means operable by said oscillating means to vary the resistance of said variable resistance elements.

EUGENE McDERMOTT.

April 3, 1951 E. M. DELORAINE ET AL 2,546,984

COMMUNICATION SYSTEM

Filed April 2, 1947

Fig. 1.

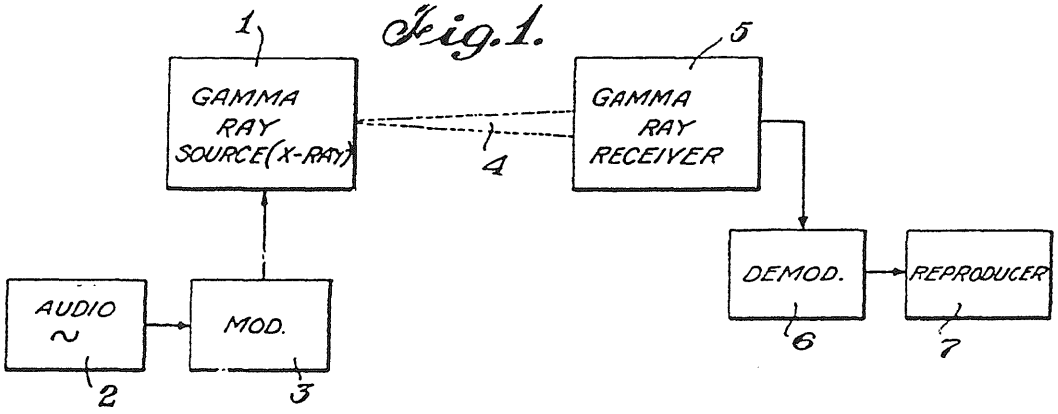


Fig. 2.

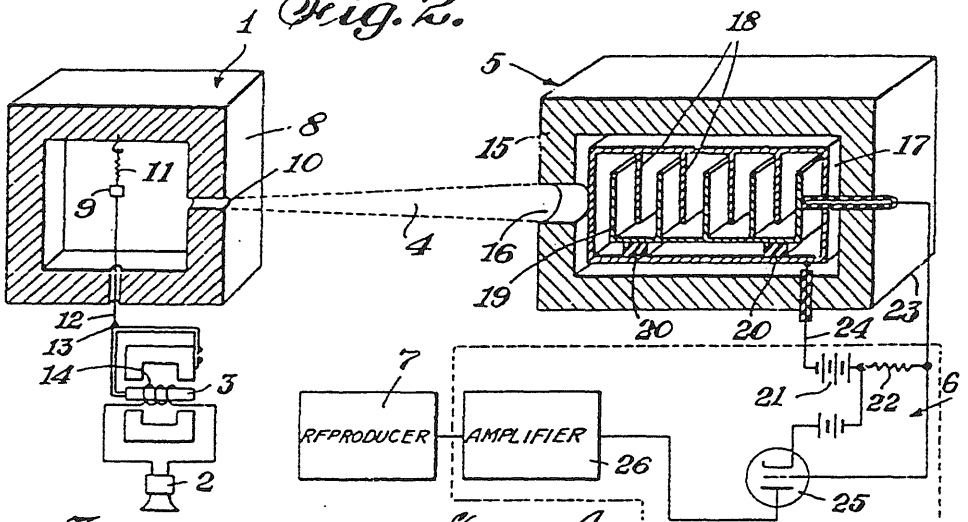


Fig. 3.

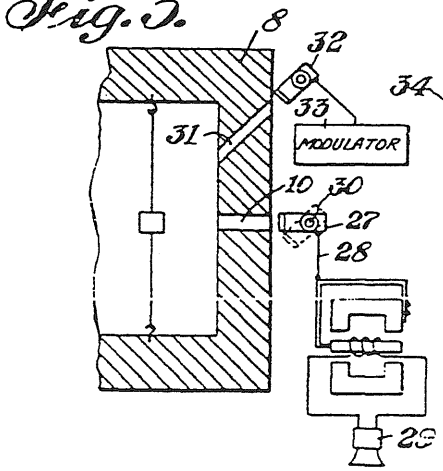
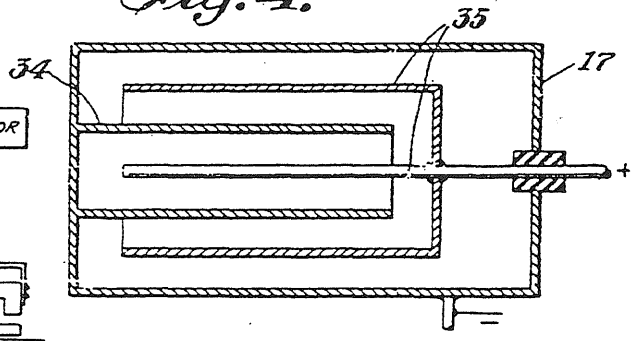


Fig. 4.



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2,546,984

COMMUNICATION SYSTEM

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Application April 2, 1947, Serial No. 738,774

6 Claims. (Cl. 250—1)

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This invention relates to communication systems and more precisely to communication systems for transmission and/or reception utilizing high energy rays corresponding to high voltage X-rays or gamma ray radiation, high energy neutrons or the like.

Various types of energy radiation such as the X-ray photons, gamma ray photons emitted from natural substances such as radium in the presence of its derivatives and photons radiated from artificial radio-active substances or other energy radiations such as neutrons have been used to a limited extent. For example X-rays have been used for the production of pictures and even premodulated to produce motion pictures. However, heretofore none of these radiations have been made use of for the purpose of transmitting and receiving intelligence signals and no suitable equipment for such signaling has been devised. These various types of energy radiations of sufficiently high voltage for transmission to a distance are utilized in accordance with the present invention for the transmission of such intelligence signals. The radiations of this type are designated herein as penetrating radiations or rays for want of a better generic term. Accordingly, as used in this specification this term will be understood to refer to energy transmission as above described.

It is accordingly an object of our invention to provide a communication system for radiating penetrating rays modulated in accordance with signal intelligence in combination with means for receiving these rays and means for demodulating the rays to reproduce the signal.

It is another object of our invention to provide a transmitter arrangement comprising a source of penetrating radiations having energy greater than a million electron volts together with means for signal modulating this radiation.

It is a further object of our invention to provide a receiver for modulated penetrating ray energy including means for producing electrical energy in response to the received penetrating energy and means for reproducing demodulations from this electrical energy.

It is a still further object of our invention to provide a transmitter wherein a source of penetrating ray energy such as radium in the presence of its derivatives or some artificial radio-active substance is provided with means for modulating the energy therefrom by means of relative movement of this primary radiating source with respect to an absorbing shutter screen.

According to a feature of our invention, energy

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may be transmitted from some source of radiation and signal modulated in accordance with this source with desired signals. The signal modulation may be made in the case of a radiating body by surrounding the body with an absorbing shield of metal provided with a small radiating opening and moving the radiated body with respect to the opening so that the walls of the chamber serve substantially as a shutter. Alternatively, a shutter of metal may be provided in front of the opening and moved in accordance with the signaling intelligence. A further alternative source may be a high voltage X-ray tube or other type of accelerating means such as the "betatron" in which is provided signal modulating means for modulating the energy and intensity of the beam.

The receiving equipment may constitute an ionization chamber wherein the rays which penetrate the cylinder will produce therein electrical energy. Possibly instead of utilizing a reduction of pressure, increased gas pressure may be provided whereby greater ionization is provided at higher voltage differences between the elements of such chamber. This voltage difference may then be amplified by any suitable means so as to reproduce signal currents equivalent to the modulated energy received within the equipment. If desired, an absorbing screen or shield may be provided substantially surrounding the receiver except for an opening directed toward the transmitting arrangement so that stray radiations will be reduced in the receiving equipment. Furthermore, the capacity of the receiving equipment unit is so proportioned with respect to the resistance of the system that a time constant sufficiently low to carry the highest frequency modulation energy is provided.

While we have described above the objects and features of our invention, a better understanding thereof as well as other objects and features will become apparent from the particular description thereof made with reference to the accompanying drawings, in which:

Fig. 1 is a block circuit diagram of a complete communication system in accordance with our invention;

Fig. 2 is a partially schematic illustration also partly in section and perspective illustrating a form of transmitter and receiver unit constructed in accordance with the principles of our invention;

Fig. 3 is a fragmentary view of a modified form of transmitter arrangement in accordance with our invention, and;

Fig. 4 is a cross sectional view of an alternative form of energy ray receiving chamber in accordance with the features of our invention.

Turning first to Fig. 1, reference character 1 refers to a source of penetrating radiation which may be a primary source of radiation either natural or artificial or may be some accelerating or generating equipment such as an X-ray tube or a betatron or other type of particle accelerating device. Energy from a signal source 2 may be applied through a modulating means 3 to the primary radiating source 1 to signal modulate the energy beam transmitted therefrom. This energy beam indicated by reference character 4 may be transmitted through space to receiving equipment 5. This receiving equipment 5 is preferably of the type which will serve to translate the received energy rays into some desired form of electrical energy. The electrical energy then is applied to demodulating or amplifying device 6 which may serve to demodulate the received energy or simply to amplify it to reproduce output signal energy. This output signal energy may then be applied to any desired reproducer such as indicated at 7.

In Fig. 2 is illustrated more specifically a particular form of modulator utilizing a primary radiating source of energy. In this system the source or transmitter 1 may comprise, for example, a rectangular box 8 made of some shielding material. The walls of the box 8 are made of sufficient thickness to absorb an optimum portion of energy radiated directly from the primary radiating source 9 mounted therewithin. An opening 10 is provided in the walls of shield 8. The source 9 is preferably spring suspended by some resilient means such as 11 within the chamber so that it is free to move longitudinally into and out of radiating position with respect to opening 10. A rod 12 extends through the lower wall of chamber 1 to electromagnetic plunger 13 which, together with coils 14, form the modulating means 3. The signal energy applied through source 2 will cause rod 12 to move upward or downward bringing the primary radiating source into or away from the opening 10 thus providing a signal modulation of the energy to be transmitted. While we have shown a simplified form of modulation circuit it will be clear that more elaborate systems using the principles known in radio art may be used without departure from the scope of our invention. Since these form no part of the present invention they have been omitted for the interest of simplicity.

At the receiver 5 the primary responsive equipment may be housed within a shielding wall 15 of an energy absorbing material to protect the apparatus from stray radiations. An opening 16 in the wall 15 may be aligned substantially with the opening 10 at the transmitter to admit the modulated rays readily into the casing. Within casing 15 is mounted a closed container 17 provided with capacitive elements 18 extending downwardly into the chamber formed within. A second set of plates capacitively associated with plates 18 is shown at 19 mounted in insulated relations to the walls of chamber 17 by means of insulating blocks 20. A source of potential 21 is coupled in series with a high resistor 22 and over lines 23 and 24 to the respective plates 18 and 19 of the chamber. The capacitive reactance of plates 18 and 19 and the resistance value of resistance 22 are so chosen that the time constant of this circuit will be sufficiently small to take care of variations of frequency of the received modulation. The rays penetrating within chamber 17 produce secondary emission from the walls of the chamber and the extended plates 18 and 19 and ionize the gas contained within the chamber rendering it conductive. By utilizing relatively high pressure of gas within this chamber the ionization may be relatively high. By reason of the potential difference between plates 18 and 19, the released electrons and negative ions will be attracted toward the positive plates and the positive ions to the negative plates producing a current flow to resistor 22 varying in accordance with the modulation of the received energy radiation means. A coupling tube 25 has its input coupled across resistor 22 and its output coupled to amplifier 25. Thus the variation in voltage produced in resistor 22 will be applied to amplifier 25 and from there the amplified energy may be applied to reproducer 7.

In Figure 3 is shown another alternative form of transmitter circuit. In accordance with this arrangement the energy source 9 is not movably suspended but is mounted in a fixed relation in front of opening 10. A shutter element 27 is mounted in front of opening 10 and controlled by some means 28 such as microphone element 29. Movement of the diaphragm in 29 through the mechanism 28 may be such as to move shutter 27 with respect to opening 10. As shown in Figure 3, shutter 27 is pivoted at point 30 and is rotated around this pivot so as to vary the amount of absorbing material in front of the opening. It will be clear to those skilled in the art that other mechanisms such as means for moving shutter 30 linearly in front of the opening, or the divided shutter with means for bringing the parts together may be provided if desired. The element 30 is preferably made to have a length substantially equal to the thickness of the shielding walls of shield 8 so as to present substantially the same absorbing properties as such walls when in its normal unoperated position. Thus, upon movement of this element by voice signal, a change in absorption takes place providing a modulation of the energy emitted through opening 10 will be obtained. For transmitting in other directions additional openings such as shown at 31 and separate shutters 32 and modulator 33 may be provided.

In Figure 4 is show an alternative structural arrangement for the chamber 17. In accordance with this arrangement the capacitive wall fastened to the chamber 17 may be in the form of a cylindrical element such as shown at 34 and the alternative structure of the other capacitively related element may be a series of concentric cylindrical arrangements shown at 35. Although only a small number of such cylinders are illustrated it is clear that the number may be multiplied as desired to achieve the operations and characteristics required.

While we have described the receiver as utilizing gas under pressure thus producing an integration of the received energy, it is clear that other forms of receiver equipment may be used. For example, by using rarefied gas, the action of the circuit will be more nearly like the ordinary Geiger counter. The counter derives its energy directly from ionization within the chamber. Such counter arrangement provides essentially amplification in that the ionized particles tend to expand and ionize further particles within the chamber. The time constant of such a circuit is relatively low and the de-ionization time is also low, producing a high resolving power. There are, however, certain difficulties in the use of

such an arrangement which may render the use of gas under pressure preferable in this system. The current produced in such a system cannot be used directly in the loudspeaker even after proper amplification since it will register to a much greater extent cosmic ray pulses and other interfering phenomena. Furthermore, the Geiger counter is generally of small volume in view of the high direct current field necessary between the electrodes for amplification. This small size while minimizing the cosmic ray effect also minimizes the useful reception.

For the direct-transmission energy rays (corresponding to energies of over a million electron volts) are to be modulated by the frequency of the human voice. Accordingly, for amplitude modulation the depth of modulation should be 50% or more. For radiations of over one megavolt energy, the absorbing shutter around the transmitter and receiver should have a thickness of the order 12 millimeters' lead. This shutter may be made preferably of material of high density such as lead, gold, mercury, or iron for gamma rays. For neutrons a low density material such as paraffin, beryllium or carbon etc. may be used.

A source of gamma radiations within the desired energy range may be obtained for example, from radium contained in a sealed tube. However, due to the small quantities of radium available, it is desirable that some of the other metals which will emit gamma radiations within the desired range be used or others that will produce neutrons in the desired amount. Although there are more than 400 radio active elements known which may be artificially produced there is a much smaller number, which can be activated by neutrons and which will emit gamma rays in the required range and have a half-life period of over two months. The known elements are cobalt (Co 60), scandium (Sc 46), zinc (Zn 65), antimony (Sb 123), tantalum (Ta 182), radio active silver (Ag 108 or 110) which has 225 days half-life. There is, however, only one element of this group with half life of over one year. This element is cobalt with a mass number 60. Such cobalt has a half life range of five years and it is interesting to note that this radio active cobalt in a quantity equivalent to 100 g. of radium weighs only 7×10^{-2} grams, if it could be prepared without any carrier substance making it sufficiently light to be readily mounted in the movable source as described above. It is also clear that high voltage electron producing machines may be used as the energy sources, and may be directly modulated.

The opening in the shield for transmission purposes as described need be no more than about 1 millimeter so that the shutter arrangement likewise may be made relatively light so that it will respond to high frequency audio energies. Except for protective purposes no shield need be provided. Moreover, modulating shutters aligned in different directions may be provided, permitting multi-beam transmission from a single source.

For the gas to be used within the receiving chamber, a non-electronegative gas (rare gas) at a relatively high pressure, of 20 to 50 atmospheres of argon, for example, is preferable. Other non-electronegative gases may be considered such as N_2 or SF_6. For comparable high sensitivity SF_6 may be used at lower pressure (for example, 5 atmospheres) than either argon or nitrogen.

The electrode arrangements in the receiving chamber should be such as to provide a high field strength in order to have high speed response to the ionizing radiation. This means that the distance between electrodes should be short without conflicting with the best possible use of the energy for ionization of gases within the chamber. By utilizing a plurality of the extensions, large surface may be provided, thereby increasing the wall effect of the gamma rays. The thickness of the electrodes facing each other should be chosen for maximum yields of produced electrons. This thickness of the electrode elements will vary for different gas pressures. The closed ionization chamber may be considered as one of the circuit elements. The resistance used with the potential source is determined by the potential difference required between the electrodes of the chamber and is inversely proportional to the ionization radiation intensity. For passage of frequencies up to 400 cycles, it can be considered that the ions produced in the chamber must reach a collecting surface within at least $1/400$ of a second. The necessary field intensity for this purpose would be about 10,000 volts per centimeter. For this purpose and at this frequency it is clear that the time constant of the circuit must be smaller than $1/400$ of a second and should be at least two or three times less, that is, one thousandth of a second. Thus, the capacity of the chamber is given as C1, that of the tube as C2 and the resistance is R; the time constant will be the total capacity C multiplied by R. It is therefore seen that the high sensitivity R should be as high as possible so that for a desired time constant then the capacity C should be as small as possible.

It will be clear that in addition to the wanted signal, stray radiations will penetrate the chamber of the receiver and produce certain interference and distortion. If, however, this penetrating energy is substantially constant, it will correspond merely to a D. C. component added to the output of the system and will therefore not be difficult to be removed.

While we have disclosed generally the principles and operation of our system, it is to be distinctly understood that this specific description is given merely by way of example and that many modifications may be made without departing from the spirit thereof. It will be likewise clear that specific calculations of values for the various elements may be readily made by those skilled in the art from the known radiation phenomena and other known factors. It is therefore to be understood that the specific examples and structures described in this specification are given merely by way of example and are not to be considered as any limitations on the scope of our invention.

We claim:

1. A receiver for signal modulated penetrating rays comprising an energy absorbing shield provided with an opening in the direction from which it is desired to receive energy, inclosing a chamber of metal, a metallic member mounted within said chamber and insulated therefrom, first extensions fastened to the wall of said chamber to provide additional surface, extensions mounted on said member in capacitive relation to said first extensions, a non-electronegative gas within said chamber, a high resistance, a source of direct potential coupled in series with said high resistance between said member and said chamber, said resistance being of such a value with respect to the capacity of said system as to provide a time con-

stant lower than the frequency of received signals, an amplifier coupled across said resistance and reproducing means coupled to said amplifier.

2. A receiver for signal modulated penetrating energy rays comprising an energy absorbing shield provided with an opening in the direction from which it is desired to receive energy, inclosing a chamber of metal, a metallic member mounted within said chamber and insulated therefrom, first extensions fastened to the wall of said chamber to provide additional surface, extensions mounted on said member in capacitive relation to said first extensions, a non-electronegative gas at a pressure greater than 5 atmospheres within said chamber, a high resistance, a source of direct potential coupled in series with said high resistance between said member and said chamber, said resistance being of such a value with respect to the capacity of said system as to provide a time constant lower than the frequency of received signals, an amplifier coupled across said resistance, and reproducing means coupled to said amplifier.

3. A receiver for signal modulated nuclear energy rays comprising an energy absorbing shield provided with an opening in the direction from which it is desired to receive energy, inclosing a chamber of metal, a metallic member mounted within said chamber and insulated therefrom, substantially planar first extensions fastened to the wall of said chamber to provide additional surface, substantially planar extensions mounted on said member parallel to and in capacitive relation with said first extensions, a non-electronegative gas within said chamber, a high resistance, a source of direct potential coupled in series with said high resistance between said member and said chamber, said resistance being of such a value with respect to the capacity of said system as to provide a time constant higher than the frequency of received signals, an amplifier coupled across said resistance, and reproducing means coupled to said amplifier.

4. A signalling system comprising a source of penetrating radiation having energy greater than a million electron volts and means for signal modulating said radiation, said means for modulating comprising an absorbing shield provided with an opening and surrounding said source, and means for controlling the position of said source relative to said opening.

5. A communication system comprising a radioactive source of high energy penetrating energy emissions, having a half-life period over two months and means for signal modulating said radiations, said means for modulation comprising an absorbing shield substantially surrounding said source, and provided with a small opening, and means for controlling the position of said source relative to said opening in response to said signals.

6. A communication system comprising a radioactive source of high energy photon emissions, comprising cobalt 60, and means for signal modulating said radiations, said means for modulating comprising an absorbing shield of lead having a thickness of at least twelve millimeters substantially surrounding said source, and provided with an opening of about one millimeter in diameter, and means for controlling the position of said source relative to said opening in response to said signals.

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LADISLAS GOLDSTEIN.

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Sept. 7, 1954 F. FUA 2,688,702

X-RAY TESTING AND MEASURING METHOD AND APPARATUS

Filed March 14, 1950

FIG. 1

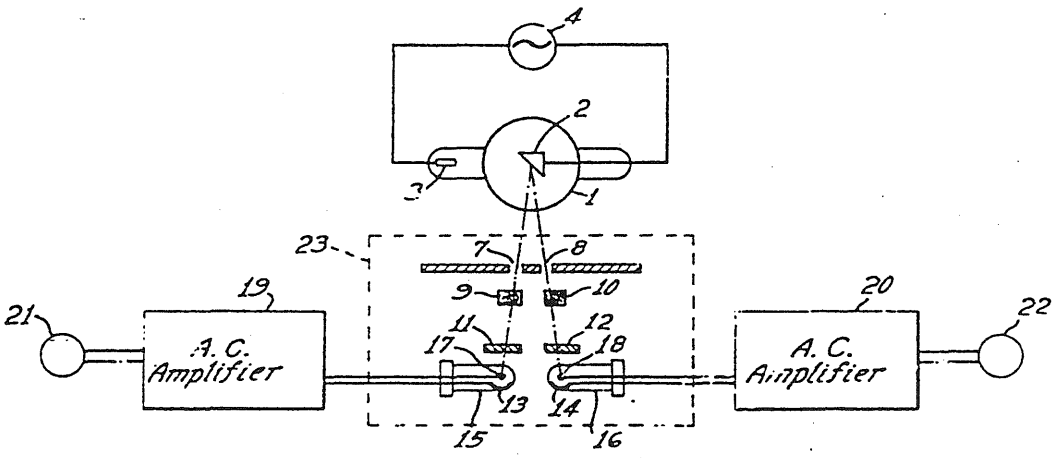
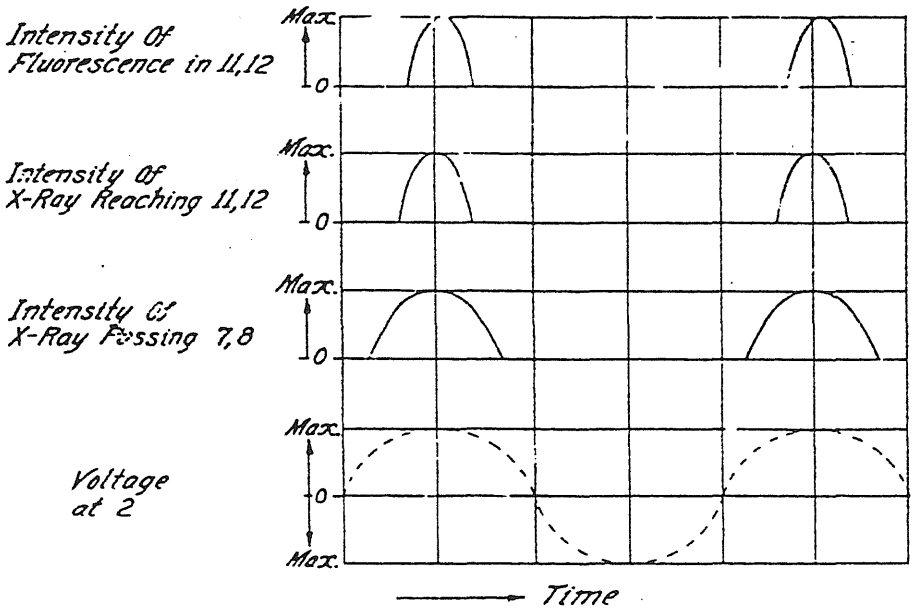


FIG. 2



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Patented Sept. 7, 1954

2,688,702

UNITED STATES PATENT OFFICE

2,688,702

X-RAY TESTING AND MEASURING METHOD AND APPARATUS

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Original application November 1, 1944, Serial No. 561,361. Divided and this application March 14, 1950, Serial No. 149,515

5 Claims. (Cl. 250—71)

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This application is a division of my copending application Serial No. 561,361, filed November 1, 1944.

This invention relates to X-ray devices and more especially to such systems using electron tube amplifiers controlled by an X-ray beam.

A principal object of the invention is to provide a specially designed testing system using X-rays, wherein the response to the X-ray excitation can be amplified with great stability and sensitivity.

Heretofore, in testing and measuring systems using X-rays as an excitation source, variations in the power supply for the X-ray tube have usually been considered a source of trouble. For example, where the anode or target voltage of the X-ray tube is derived from a rectified and filtered A. C. power supply line, any imperfect filtering has been considered a drawback to be sedulously avoided. It has likewise been considered a drawback that the X-ray tube be energized by raw A. C. Where the output of the X-ray tube exhibits an A. C. component, there results a variable width of the resultant X-ray spectrum and a corresponding variation in the X-ray intensity.

It is a principal object of this invention to utilize the alternating current component of the X-ray excitation as a useful adjunct to enable the excitation response to be translated and amplified by stable and highly selective alternating current amplifiers.

Another object is to provide a method of translating and amplifying the X-ray excitation response for the purpose of increasing the sensitivity of the testing or measuring system as a whole.

A feature of the invention relates to an improved system for testing uniformity or the lack of uniformity of articles through the intermediary of an X-ray source and an electric wave amplifier.

Another feature relates to a method of using an X-ray tube as a testing source in conjunction with a stable alternating current electron tube amplifier.

A still further feature relates to the novel organization, arrangement and relative location of parts which cooperate to produce an improved and more sensitive X-ray measuring and testing system.

Other features and advantages not specifically enumerated will be apparent after a consideration of the following detailed description and the appended claims.

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In the drawings:

Fig. 1 shows diagrammatically an X-ray activated measuring device according to the invention; and

Fig. 2 illustrates graphically the operation of the invention in terms of voltage, X-ray beam intensity or signal intensity excited by the X-ray beam at various points in the device of Fig. 1.

When an X-ray tube is subjected to a cyclically variable power supply for the anode or target voltage, the output of the X-ray tube will vary correspondingly in frequency and in intensity. If this output impinges on a suitable X-ray responsive screen such as a fluorescent screen, the light emitted by the screen will vary in consonance with the X-ray variations, except for the inherent time lag of the fluorescent material. If the light from the screen is projected on a photoelectric cell or the like, the time lag in the fluorescent screen will tend to displace the instants of maximum and minimum excitation of the electron tube amplifier connected to the photoelectric cell, and the non-linearity of response of the fluorescent screen to X-ray excitations of different amplitude, will tend to reduce the difference between the said maximum and minimum amplifier excitation.

However, for a given X-ray tube operating with a certain voltage-time characteristic of the target or anode supply, during each of the successive cycles of variation of that supply, all other factors remaining the same, both the frequency spectrum and the intensity output of the X-ray tube will vary in the same manner. That is to say the frequency of the X-ray spectrum and its intensity-versus-time will vary with the cyclical variation in the anode voltage supply. Therefore, the X-ray excitation of a fluorescent screen detector will follow an identical pattern during the successive cycles and will transmit identical excitations to an electron tube amplifier connected to the detector and the peak, mean, or average values of these excitations, will remain identical over successive cycles.

These excitations being regularly recurrent and continuously variable over each cycle, are in accordance with the present invention, amplified by an electron tube amplifier of the alternating current type which can be designed so as to be sufficiently selective to respond only to a very narrow frequency band corresponding to the frequency of excitation of the X-ray responsive fluorescent screen. This results in a corresponding decrease in the noise level of the amplifier and an increased non-responsiveness to

extraneous undesirable excitations. These phenomena are graphically indicated in Fig. 2, with reference to the particular apparatus of Fig. 1.

If, however, with an X-ray tube energized as above mentioned the intensity of the beam exciting the X-ray fluorescent screen is modulated or changed to a new value by the introduction of an absorbing medium in the X-ray path, the peak, mean or average value of the excitation voltage impressed on the amplifier over each cycle will vary and this will correspondingly vary the output of the amplifier. Therefore, the peak, mean or average value of this amplified signal can be used, as a measure of the absorption of the inserted medium, this measurement being either in absolute or relative values.

Such an arrangement is schematically illustrated in Fig. 1 of the drawing, wherein there is represented any well-known form of X-ray tube 1, the anode or target 2 and the cathode 3 of which are supplied with power from an A. C. supply source 4. The current through the X-ray tube under these circumstances will be a pulsating, intermittent direct current having a regularly recurrent component.

The X-ray beam from tube 1 is passed through a plurality of slits 7, 8, in alignment with which are two materials 9, 10, one of which may be a standard of known density or X-ray absorption power, and the other of which may be a material whose density or absorption power is to be compared with the standard. The divided beam, after passage through the bodies 9 and 10, impinges on two respective screens 11, 12, which have the property of becoming fluorescent under X-ray excitation. These screens may be of any construction well-known in the X-ray art. The fluorescent light from each of the screens 11 and 12 is projected upon the photosensitive cathodes 13, 14, of a corresponding pair of photoelectric cells 15, 16, whose anodes are respectively 17 and 18. The cells 15 and 16 are connected to respective alternating current amplifiers 19, 20, whose amplified outputs are applied respectively to suitable meters or indicators 21, 22. In accordance with the invention, the amplifiers 19 and 20 are tuned so as to have a greater sensitivity at approximately the frequency of the A. C. supply source 4. With this arrangement, the amplifiers 19 and 20 may be designed with the requisite stability and high gain so as to enable very much smaller variations between the divided portions of the X-ray beam to be detected. For typical descriptions of a suitable organization of testing apparatus in which the system of Fig. 1 may be embodied, reference may be had to the copending Fua and Woods application Serial No. 558,928, filed October 16, 1944. Since the sensitivity of the narrow band alternating current amplifier 19, 20, can be extremely high before reaching the noise level, and as the gain of such an A. C. amplifier is much less responsive to voltage supply level variations and other extraneous variations, than is a D. C. amplifier, the combination of an X-ray beam cyclically varied, and an A. C. amplifier as disclosed in Fig. 1, will give an overall sensitivity not obtainable heretofore in the detection and measurement of very weak X-rays.

The various meters or indicators 21, 22 can be calibrated under control of a suitable calibrated gain control in the respective A. C. amplifiers, which gain controls can be designed and calibrated in terms of X-ray intensities or relative or absolute absorption powers of articles to be subjected to the X-ray excitation. Instead of using two separate meters 21 and 22 as in Fig. 1, the outputs of the amplifiers 19 and 20 can be fed in opposition to a single meter. No reading, therefore, will appear on this meter as long as the two screens 11 and 12 are equally excited and if the gains of the amplifiers 19 and 20 are correctly balanced. If, however, an absorption medium 10 of any kind is placed in the path of one of the beams, a definite reading will show in the output meter and this will be a measure of the X-ray intensity striking screen 12 as compared to the steady excited screen 11. Such an arrangement has the advantage that the equipment is intensitive to fluctuations which affect the two portions of the divided beam equally.

It will be clear from the foregoing that, if desired, the alternating power supply 4 may be a specially designed A. C. power source having a frequency which is well removed from any disturbing frequencies. For example, if source 4 is of 25 cycles the equipment may be used quite close to powerful 60 cycle sources without introducing disturbances. In this event, of course, the amplifiers 19 and 20 will be designed to have a band pass characteristic between 20 and 30 cycles and, if desired, with a rejection filter for the 60 cycles.

I claim:

1. Apparatus for the testing of material by the precise and accurate measurement of X-ray penetrating the material including, in combination, an X-ray tube having conventional heated cathode and target anode, a source of alternating current of predetermined frequency and voltage impressed across said cathode and anode, means for interposing material to be tested in the path of an X-ray beam from said tube, a fluorescent screen in the path of said beam beyond said material from said tube, an electron-emissive photocell responsive to fluorescence of said screen, an alternating current amplifier tuned to have a narrow band-pass corresponding to said frequency, said amplifier receiving the output of said photocell as input, and a quantitatively responsive meter for measuring the amplitude of the peaks of the output of said amplifier.

2. The method of detecting and precisely and accurately measuring small variations in the X-ray opacity of materials which includes feeding an X-ray source with an alternating current power supply, receiving a beam of X-ray from said source passed through the material to be tested upon a fluorescent screen, permitting the fluorescence of said screen to activate an electron-emissive photocell, feeding the output of said photocell to a highly selective alternating current amplifier, tuning said amplifier to have a narrow band-pass corresponding to the frequency of said power supply, and precisely measuring the amplitude of the peaks of the output of said amplifier.

3. Apparatus for precisely and accurately measuring the X-ray opacity along a given path through an object to be measured which includes an X-ray tube having conventional heated cathode and target anode, a source of alternating current of predetermined frequency and voltage impressed across said cathode and anode, means for passing a beam of X-ray from said tube through the object to be measured, a fluorescent screen arranged to receive said beam after its passage through said object, an electron-emissive photocell arranged to receive the fluorescence from said

a comparison standard electric current having settable values of an order comparable to those of the output current of said photocell, alternating current amplifying means responsive to said comparison current and said output current connected to said amplifying means between said comparison current and said output current, and indicator means connected to said amplifying means for indicating the sign and magnitude of the difference between said comparison current and said output current.

4. Apparatus for precisely and accurately comparing physical characteristics of a material with a standard sample of said material which includes an X-ray tube having conventional heated cathode and target anode, a source of alternating current of predetermined frequency and voltage impressed across said cathode and anode, means for defining two separate beams of X-ray from said tube, means for passing one of said beams through the material to be compared, means for passing the other of said beams through the standard sample, a first fluorescent screen arranged to receive the beam passing through the material to be compared, a second fluorescent screen arranged to receive the beam passing through the standard sample, a first electron-emissive photocell arranged to receive the fluorescence of said first screen, a second electron-emissive photocell arranged to receive the fluorescence of said second screen, alternating current amplifying means responsive to the outputs of said photocells, and indicator means connected to said amplifying means for indicating the difference between said output currents.

5. Apparatus for precisely and accurately measuring the thickness of a moving web including, in combination, an X-ray tube having conventional heated cathode and target anode, a source of alternating current of predetermined frequency

and voltage impressed across said cathode and anode, means for defining two separate beams of X-ray from said tube, means for conducting the web across the path of one of said beams, means for interposing a standard sample of the web being measured in the path of the other of said beams, a first fluorescent screen arranged to receive the beam passing through the moving web, a second fluorescent screen arranged to receive the beam passing through the standard sample, a first electron-emissive photocell arranged to receive the fluorescence of said first screen, a second electron-emissive photocell arranged to receive the fluorescence of said second screen, alternating current amplifier means responsive to the outputs of said photocells, and indicator means responsive to the output of said amplifier means for indicating the difference between said outputs.

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Certificate of Correction

Patent No. 2,688,702 September 7, 1954

Frederic Fua

It is hereby certified that error appears in the printed specification of the above numbered patent requiring correction as follows:

Column 4, line 15, for "intensitive" read *insensitive*;

and that the said Letters Patent should be read as corrected above.

Signed and sealed this 26th day of October, A. D. 1954.

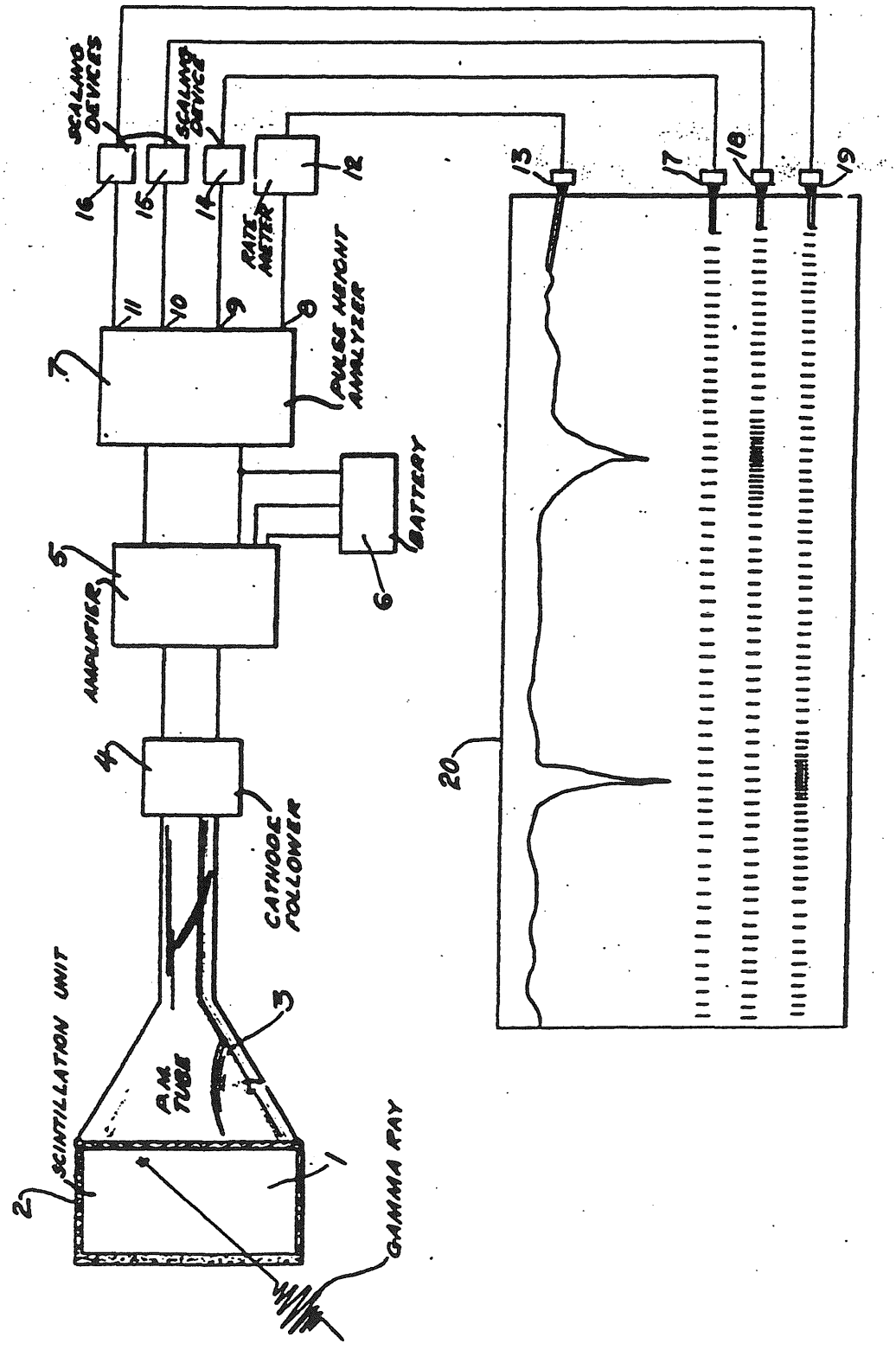
[SEAL]

ARTHUR W. CROCKER,
Assistant Commissioner of Patents.

July 28, 1959 H. T. F. LUNDBERG ET AL 2,897,368

AERIAL GEOPHYSICAL EXPLORATION WITH SCINTILLATION SPECTROMETER

Filed March 18, 1954



United States Patent Office

2,897,368
Patented July 28, 1959

2,897,368

AERIAL GEOPHYSICAL EXPLORATION WITH SCINTILLATION SPECTROMETER

Hans T. F. Lundberg, Toronto, Ontario, and Robert W. Pringle, Kenneth I. Roulston, and George M. Brownell, Winnipeg, Manitoba, Canada

Application March 18, 1954, Serial No. 417,154

7 Claims. (Cl. 250—71)

This invention relates to an instrument for aerial geophysical exploration with a scintillation spectrometer, and has for an object to locate mineral deposits, such as ores, oil and gas, through providing for the identification of radioactive substances from an aircraft by pulse height sorting of the effects of their gamma rays.

Another object is to provide for separating the effects of radium, thorium, and potassium on the basis of their gamma ray spectra.

Another object is to provide for the counting of events at, or above, a certain energy band, or level, which is characteristic of a selected source of gamma rays.

Another object is to provide for simultaneously receiving and recording the amplitude of total gamma ray intensity from the earth's surface in terrain under investigation, as well as variations (preferably modulated) in gamma ray intensity derived from different sources such as radium, thorium and potassium, singly and/or in combination.

Another object is to provide an instrument for the hereinabove stated purpose which includes scintillation means, photomultiplier means, and amplifying means, adapted to be connected with a suitable source of electric power, together with pulse height analyzing means having an output fitted with a rate meter for indicating the total gamma ray variations in terms of amplitude, i.e., an integral discriminator output; and also having, at least one, preferably several differential discriminator outputs each advantageously fitted with a scaling device for indicating the gamma ray variations emanating or derived from individual or multiple sources, e.g., thorium, radium and thorium, and potassium.

Another object is to furnish the integral output with a continuously acting tracer recording pen, and to furnish the differential outputs with intermittently acting relay pens whereby there may be imposed upon the recorder tape a continuous delineation of the integral amplitude variations due to anomalies, as well as complementary opposed dash lines expressing as density the differential variations related to separate sources of the gamma rays.

Another object is to achieve simplicity in the construction and operation of the instrument as well as to render the instrument easily portable and eminently suited to transportation by, and operation during the flight of, an aircraft.

A further object is to provide certain improvements in the form, construction and arrangement of the parts of the instrument, thus effectively attaining the above recited objects and others inherent in the invention.

In brief summary, the invention envisages an instrument for aerial geophysical explorations which embodies means, preferably a unit, that has the characteristic capacity of producing light photon scintillations as a result of the impact of gamma ray energy; the said means operatively connected with a device, such as a photomultiplier tube, which is designed and adapted to accept the scintillations and convert them into photo-electron voltage pulses. Means for amplifying said pulses to increase their voltage is in operative association with the output of the photomultiplier, and a device, which may be defined as a pulse height analyser or discriminator is, in turn, connected with the amplifier. This analyser is fitted with several outputs, one for the function of integral discrimination or total gamma rays intensity variation recording; and the others, preferably three, to serve as differential discriminators and record gamma ray variations attributable to particular sources, preferably, thorium alone, radium and thorium, and potassium alone. The integral output desirably performs through a rate meter device, while the differential outputs preferably act through scaling devices. A recording tape is appropriately fed and pens associated with the several outputs visually inscribe on the tape variations in the above named gamma ray effects due to the presence of anomalies in the terrain being explored. It is preferred to use a tracer pen for the integral output and relay pens for the differential outputs. Flights of the aircraft carrying the instrument are made over the terrain along predetermined profiles, in substantial parallelism and, if desired, crossing, at advantageous constant heights e.g., between two hundred and three hundred fifty feet, and the recordings obtained are appropriately processed, adjusted to linear scale, plotted, and interpreted as to significant indications. The effect of contamination rays from e.g., fluorescent dials, should be carefully avoided, as by shielding; but the instrument is so efficient in detecting gamma rays that cosmic rays, of which the freqeuncy is low, may be regarded as relatively negligible.

This invention may be considered as an extension or development of the subject matter of U.S. Patent No. 2,686,266, issued August 10, 1954 to Robert W. Pringle, Kenneth I. Roulston and George M. Brownell.

A practical embodiment of the instrument is diagrammatically represented in the accompanying drawing to which reference will now be made.

The scintillation means, here shown as a phosphor unit, is denoted by 1, and may be composed of any suitable substance having the above mentioned capacity of responding with the emission of light photon scintillations when bombarded by or under the impact of gamma rays. Examples may be cited as sodium iodide activated with thallium; cesium iodide activated with thallium; anthracene; and plastic or liquid scintillators, especially if these contain heavy elements such as mercury. The first named has been found to give excellent results. It should be of large size, to give adequate sensitivity of detection, and must have a thickness greater than the range of secondary particles produced by the gamma radiation in the phosphor. This latter condition is necessary if the device is to act as a proportional counter and give a measure of the gamma ray energy. The perimeter and one face of the phosphor unit are advantageously coated with a layer 2, such as magnesium oxide, which functions as a light scatterer. If sodium iodide is used, care must be taken to protect the phosphor against the effects of moisture. If preferred, the scintillating unit may be in liquid form confined within a suitable container.

The face of the unit that is uncoated with magnesium oxide, or other reflector, is secured to that end of a photomultiplier tube 3 which is distant from its base and cathode follower 4, the preferred adhesive being a silicone oil which provides an optical bond. The tube 3 may be selected from those available on the market, it being desirable to choose one of very high efficiency especially with respect to multiplication and amplification; and its cathode is formed with the usual photosensitive surface which, when illuminated by scintillations from the unit 1, converts the same into current or

voltage pulses, which latter are amplified by the multiplier component of the tube in a well understood manner.

An amplifier 5, which may be of conventional type, e.g., linear, is electrically connected to the output of the photomultiplier tube and serves materially to increase the voltage of the pulses emitted by the tube. Electric power is supplied by a battery 6 that is in circuit connection with both the tube and the amplifier. A small but adequately powerful, e.g., one thousand volt, battery is highly desirable, such as the nickel cadmium alkaline type, for the photomultiplier. Alternatively, power may be obtained from any available source, conveniently the electrical system of the aircraft in which the instrument is carried.

The output of the amplifier 5 is led to a discriminating device in the form of a pulse height analyser denoted by 7. Such a device is fully disclosed in the above mentioned Patent No. 2,686,266, and it is deemed unnecessary to detail the same herein; though it may be generally characterized as embodying a "flip-flop" or univibrator circuit including a detector and a discriminator the tubes of which are normally in a stable condition which increase of voltage changes to unstable and then causes a "flip" over to a meta-stable condition that continues until change in voltage re-establishes instability and causes a "flop" back to stability. The pulse required to effect this action is termed a "trigger" pulse and will vary with the bias setting of the device, thus permitting discrimination against pulses below any selected amplitude or height.

The analyser or discriminator 7 is fitted with four outputs 8, 9, 10 and 11. Output 8 provides an integral discrimination of total gamma ray intensity in amplitude, and is in electrical connection with a rate meter 12. This device is also fully disclosed in the above named Patent No. 2,686,266, and it is believed sufficient to note that it takes the form of a micro-ammeter which indicates average current passing through one tube of the "flip-flop" circuit and presents a reading that is proportional to the rate at which pulses are accepted by the "flip-flop" circuit. By suitable adjustment, the time during which the rate meter averages the current may varied. The output of the rate meter is connected to a recording device, preferably in the form of a tracer pen 13, adapted to inscribe a continuous line on a recorder tape.

Having in mind the fact that the functioning of the scintillation spectrometer is based on the proportionality between the energy of a gamma ray event occurring in the sensitive component of the instrument and the voltage output from the latter, it is evident that means and method of pulse height sorting is needed if the instrument is to provide full information as a gamma ray spectrometer. It is also an important, if not essential, requirement that the means for this accomplishment in aerial exploration incorporate simplicity in design and demand a minimum of servicing. The pulse height sorting is also affected by the known facts that the gamma ray spectrum from potassium consists of a single line at 1.47 Mev. (million electron volts); while the spectra from radium and thorium are complex and consist of numerous lines extending in the case of radium to a weak line at 2.20 Mev., and in the case of thorium to a strong line at 2.62 Mev. Accordingly, the effect of potassium can be eliminated through a bias setting of the analyser above 1.50 Mev. while leaving the latter responsive to the combined effects of radium and thorium each of which is characterized by a plurality of lines above such a setting. Likewise, it will be clear that enhancement of the effect of potassium may be achieved by a bias setting at or close to 1.47 Mev. where its spectrum is centered.

With the foregoing observations in mind, our invention contemplates provision for identification of the above named individual elements through recordings made while in flight, by combining with the pulse height analyser, in addition to its integral discriminator output 8 and the rate meter 12, the plurality, three being shown, of differential outputs, denoted by 9, 10 and 11; each of the latter preferably being electrically connected with a scaling device to demodulate (or demultiply) the pulses from the said three outputs. The scaling devices for outputs 9, 10, 11, are marked 14, 15, 16, respectively; and each is, in turn, in operative electrical connection with suitable visual recording means that preferably comprises a relay and its pen designed to act intermittently and inscribe a row of discrete dash lines on a recorder tape that is moved in contact with the pens. In the drawing the relays and their pens are indicated by 17, 18, 19, and the recorder tape by 20.

The construction and mode of operation of scaling devices called "scale of two" is understood by those skilled in electrical engineering, but it may be pertinent to recite that the device embodies a biased multivibrator circuit with a diode input for triggering its action. In each of our devices 14, 15, 16, we have combined four such "scale of two" units with the output of the last unit fed to an additional multivibrator that presents a current pulse of sufficient power to operate the pen relay. Thus our form of scaling device produces one output pulse for each sixteen pulses fed to it and may be denominated a "scale of sixteen" unit. Its purpose and function are to demultiply or demodulate, and hence statistically smooth, the output of pulses from the analyser with the result of inscribing on the tape 20 density type markings that are easily read. In order to adapt the instrument to a wide range of pulse counting rates, the scaling devices are so arranged that each may be operated on a scale of two, four, eight or sixteen.

It will be observed from the drawing that the inscriptions of the tracer pen 13 and relay pens 17, 18, 19, are opposed or aligned so as to complement each other and, being simultaneously produced, they enable constant visual observation of their significance as well as providing permanent indications for study and processing.

Briefly summarizing the operation of the instrument; gamma rays (one being indicated on the drawing) from the earth's surface, as the aircraft carrying the instrument passes thereover, impinge upon and penetrate the phosphor 1, which latter responds with scintillations that are received by the photomultiplier tube 3, converted into photo-electrons that are multiplied in number to produce voltage pulses which are increased by the amplifier 5. These voltage pulses are transmitted to the pulse height analyser 7 which is equipped with four outputs; one for integral discrimination, followed by amplitude recording of total gamma ray intensity, and the other three for differential discrimination, followed by density recording, of gamma ray intensity from selected sources. It has been found practical and successfully useful to select as these sources thorium alone, radium and thorium together, and potassium alone. These sources are identified in terms of their characteristic gamma ray spectra. The integral amplitude discrimination is fed through the rate meter 12 and inscribed on the tape 20 by the tracer pen 13 as a line of intensity, while the differential discriminations are fed through the scaling devices, demodulated or demultiplied thereby, and inscribed on the tape 20 as rows of dash lines indicating density. The record of the several indications thus simultaneously produced is in such form that all the markings complement each other and present the whole significant picture. The pulse height analyser is adjustable to various spectrum ranges to record variations due to anomalies in the effects of chosen sources; while the scaling devices are also adjustable in respect to demodulation and/or demultiplying; and the record obtained supplies desired information with respect to the presence, location, and identification of the sought for elements or substances.

Referring to the drawing, the relay pen 17 may be considered as recording effects of thorium alone, pen 18 as

recording effects of radium and thorium together, and pen 19 as recording effects of potassium alone. It will thus be observed that a notable density recording by pen 18 is aligned with one peak in the tracer line of pen 13; while a notable density recording by pen 19 is aligned with a second peak in the line of pen 13, thereby indicating the sources of the effects causing the said peaks.

In this connection, it is deemed pertinent to point out that the radioactive so called "halo" which is known to surround oil and/or gas deposits, consists of radium-uranium effects, and that, accordingly, the capacity of the present invention relating to the detection of particular sources of gamma radiation renders it peculiarly and admirably suited to exploration for oil and/or gas because of the facts just stated as well as the inherent characteristics of the invention in general.

The instrument is simple in design and construction, readily portable, requires a minimum of servicing, and is admirably suited to aerial exploration.

If conditions so dictate, efficiency of the instrument may be promoted by the use of a plurality of scintillation units and photomultiplier tubes in combination with the other components of the instrument.

We desire it to be understood that various changes may be resorted to in the form, construction, arrangement and material of the instrument without departing from the spirit or scope of the invention; and hence we do not intend to be limited to details herein shown or described except as they may be included in the claims or be required by disclosures of the prior art.

What we claim is:

1. An instrument designed and adapted for aerial geophysical exploration in the search for and identification of mineral deposits such as ores, oil and gas comprising, means for reacting to the impact of gamma rays from the earth's surface by the production of photon scintillations, photomultiplier means operatively connected with the said gamma ray reacting means for receiving such scintillations and converting them into photoelectrons sufficient to produce voltage pulses, means for amplifying said pulses, pulse height analysing means for receiving such amplified pulses and discriminating them both integrally and differentially, and means operatively connected with said analysing and discriminating means for simultaneously producing records showing both amplitude variations in total gamma ray intensity received from the terrain being explored and density variations in gamma ray intensity derived from at least one selected source of the rays in said terrain, the said scintillation means being of such size as to enable the simultaneous production of both said records and of a thickness greater than the range of secondary particles produced in said scintillation means by the gamma radiation.

2. An instrument as defined in claim 1, in which the scintillation means includes a plastic unit.

3. An instrument designed and adapted for aerial geophysical exploration in the search for and identification of mineral deposits such as ores, oil and gas comprising, means for reacting to the impact of gamma rays from the earth's surface by the production of photon scintillations, photomultiplier means operatively connected with the said gamma ray reacting means for receiving such scintillations and converting them into photoelectrons sufficient to produce voltage pulses, means for amplifying said pulses, pulse height analysing means for receiving such amplified pulses and discriminating them both integrally and differentially, and means operatively connected with said analysing and discriminating means for simultaneously producing records showing both amplitude variations in total gamma ray intensity received from the terrain being explored and density variations in gamma ray intensity derived from at least one selected source of the rays in said terrain.

4. An instrument as defined in claim 3, which includes at least one scaling device for the density recording.

5. An instrument designed and adapted for aerial geophysical exploration in the search for an identification of mineral deposits such as ores, and gas comprising, means for reacting to the impact of gamma rays from the earth's surface by the production of photon scintillations, photomultiplier means operatively connected with the said gamma ray reacting means for receiving such scintillations and converting them into photoelectrons sufficient to produce voltage pulses, means for amplifying said pulses, pulse height analysing means for receiving such amplified pulses and discriminating them both integrally and differentially, and means operatively connected with said analysing and discriminating means for simultaneously producing records showing both amplitude variations in total gamma ray intensity received from the terrain being explored and density variations in gamma ray intensity derived from at least one selected source of the rays in said terrain, the said means for producing a record of the density variations including at least one scaling device adjustable to different scales of demultiplication.

6. An instrument as defined in claim 3, in which the means for producing records is constructed and arranged to make the amplitude record in a continuous line and the density record in at least one broken line.

7. An instrument as defined in claim 6, in which the means for producing records imposes the continuous and broken lines in such relative positions that their indications are mutually complementary.

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FLUORESCENT X-RAY SCREENS

Filed June 1, 1956

FIG. 1

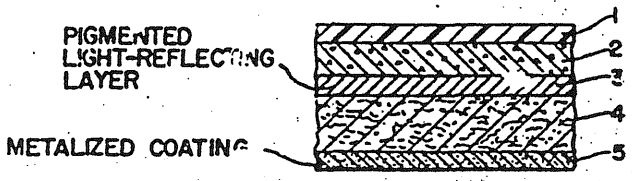


FIG. 2

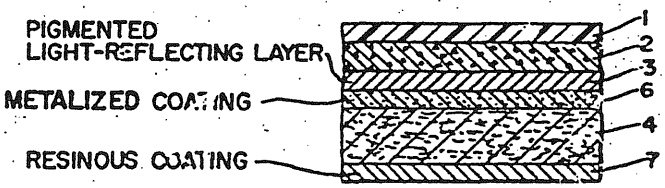


FIG. 3

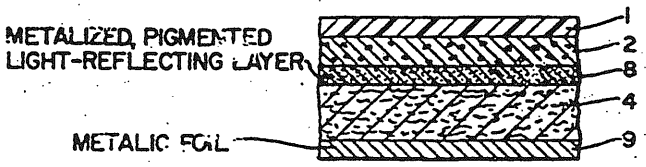


FIG. 4

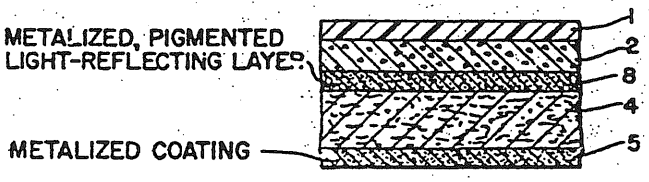
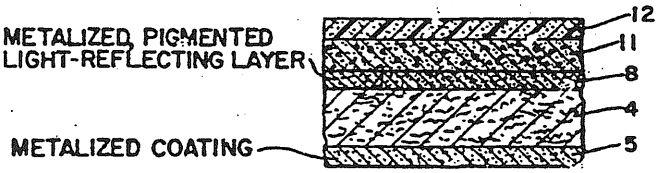


FIG. 5



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United States Patent Office

2,904,689

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2,904,689

FLUORESCENT X-RAY SCREENS

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Application June 1, 1956, Serial No. 588,723

4 Claims. (Cl. 250—80)

This invention relates to fluorescent screens employed to intensify the image produced by X-rays on a photositive film or plate. More especially the invention relates to the reduction of undesired exposure of the photosensitive emulsion by local static discharges between such screens and the film or plate.

Intensifying screens are employed to increase the exposure of the sensitized plate or film (hereinafter referred to as a "negative") without increasing the exposure time or the X-ray concentration. These screens are customarily inserted on both sides of the negative, and the resulting "sandwich" is secured in a light-tight holder known as a cassette. In exposing the negative, the X-rays pass through one side of the cassette, through one intensifying (front) screen, through the sensitized negative and thence into the fluorescent layer of the second intensifying (back) screen. This causes both screens to fluoresce, and the resulting light combines with the X-rays in exposing the negative.

Radiologists are aware of the fact that, in addition to the intentional exposure of the negative by the process above summarized X-ray negatives frequently are mottled by spurious exposures which have been found to be due to local static discharges. These discharges are more prevalent in dry climates and they appear also to be related to the materials employed in the negative and in the intensifying screen, some materials being more prone than others to the generation of static charges. Explanations of static charges and discharges and the relation of the characteristics of materials thereto, especially dielectric characteristics, are to be found in chapters on static electricity in text books on physics. In general, two types of static electricity have been observed in connection with X-ray screens and negatives or films: (1) friction static which results from relative movement (usually sliding) between the negative and the adjacent screen, and (2) pressure static which results when the screen is pressed tightly against the negative. Both types of static are discharged when the negative is separated from the screen, because the work in so doing induces a high potential difference. The friction type of static produces dark streaks or crow-foot designs on the developed negative and the pressure static produces dark spots which are usually denser than the first type, but both interfere with an accurate reading and interpretation of the radiograph. Heretofore, no successful means has been proposed to overcome the undesired exposure by static discharge.

We have discovered that this undesired exposure can be substantially reduced by introducing into the intensifying screen structure one or more discrete layers of suitable material which is electrically conductive in the manner below described, and sufficiently transparent to X-rays. It has been found that satisfactory results can be achieved by interposing separate conductive layers or by modifying previously employed layers so as to be sufficiently conductive.

The invention will be more fully understood from the following description considered in connection with the accompanying drawings in which:

Fig. 1 illustrates in cross section, an embodiment of the invention which is generally preferred because it is of simple construction and is especially effective in minimizing static discharges;

Fig. 2 is an alternative construction of an intensifying screen in which a conductive layer is interposed near the center;

Fig. 3 shows another alternative in which the pigmented light-reflecting layer is modified to comprise a conducting layer;

Fig. 4 shows a third alternative embodiment employing two layers of metallic foil; and

Fig. 5 illustrates an embodiment in which all of the layers except the backing sheet are conductive. The various layers are not drawn to scale in any of the figures.

In the preferred embodiment of Fig. 1 an intensifying screen is shown which comprises a backing and supporting sheet 4 which is coated with four different layers. Layer 2 includes a phosphor material (indicated by angular particles) which fluoresces when energized by X-rays. Layer 3 is a pigmented light-reflecting layer. Layer 1 comprises a thin protective covering layer which is substantially transparent to visible light in both directions and is arbitrarily represented by the symbol for plastic. Layer 5 comprises a metallized coating preferably of aluminum flakes secured in a binder, and is represented by stippling. The materials employed in the various mentioned layers and their relative locations are important in connection with the present invention. Consequently, the nature of the mentioned layers and the principles by which the desired results can be achieved will now be described.

The material of which the supporting or backing sheet 4 is made can be chosen from several substances having various characteristics. The better known materials are paper and certain plastics. Some plastic materials are not suitable for intensifying screens because they absorb too much X-ray energy. We presently prefer thick paper as a backing material because it has the required mechanical characteristics, viz., is firm but suitably flexible, is comparatively cheap and is highly permeable to X-rays. For the present purpose we employ paper of thickness in the range between 0.005 inch and 0.020 inch, the preferable thickness being from 0.014 inch to 0.016 inch. Substantially the only disadvantage of paper is that it is subject to absorption of moisture which tends to alter its dimensions and reduces its dielectric qualities. However, when coated in accordance with the present invention, the paper backing sheet is substantially unaffected by moisture conditions usually encountered.

Among the plastic sheet materials suitable as a backing support are cellulose acetate or nitrate, polystyrene, polymethracrylates, rubber, the polyesters and cloth of vegetable or glass fiber coated or impregnated with any of these materials. The thickness required would depend, of course, upon the characteristics of the particular material, but, in general, thicknesses of the order mentioned in connection with paper are useful. One plastic material which we have used with good success for backing sheets comprises white-pigmented polyvinyl acetate-polyvinyl chloride copolymer sheet, 0.015 inch thick.

On top of the backing layer is a pigmented reflecting layer 3 which is employed, as shown in this embodiment, for the purpose of reflecting visible light toward the photographic negative. Although some intensifying screens presently employed in the art do not include such a reflecting layer, we prefer to employ it, because it improves the overall efficiency of the screen. Its X-ray ab-

sorption is negligible, but its reflection of light on the negative is considerable. This pigmented layer comprises titanium dioxide stirred with a small amount of binder and solvent. Such a layer has high dielectric properties.

The fluorescent layer 2 may comprise any of the phosphor materials commonly employed for the purpose. Obviously, the material should be one which actively fluoresces when energized by X-rays, and should have light-emitting properties which match as closely as possible the light-sensitivity characteristics of the photographic emulsion employed in the negative. These characteristics are now well known in the art and need not be discussed here. Usually the phosphor employed comprises calcium tungstate in finely divided form and applied as a suspension in a solution of a suitable binder such as cellulose nitrate or acetate in a suitable solvent. To provide high X-ray efficiency it is preferable that a minimum amount of binder be employed, preferably less than 5% by weight calculated on the mixture. However, the less the proportion of binder material the more brittle is the layer. Consequently, there is an optimum relationship, readily ascertained, between the amount of binder required and the stiffness of the backing sheet 4. In general, flexibility is an advantage.

The cover layer 1 is for the purpose of protecting the fluorescent layer. Such a coating is customarily employed in intensifying screens and, like the fluorescent layer itself, need not be described in detail. It should be as transparent as possible to visible light, as well as X-rays, and should have a hard surface and be moisture resistant. Customarily such a layer is comprised of a solution of cellulose acetate in any suitable solvent in sufficient quantity to produce a very thin film when dry. This coating protects the phosphor surface against abrasion, dirt and moisture, and it comprises a dielectric material.

In accordance with the invention, a "conductive" layer 5 is applied to the rear surface of the backing sheet 4. Although many different conductive materials of various physical forms may be employed in this layer, we have found that aluminum appears to be the most satisfactory because, in the thickness required to produce adequate conductivity, its X-ray absorption is tolerable, it is readily available in a variety of forms, and is inexpensive.

It appears that in order to minimize the above-described effects of static discharges in undesirably exposing the photographic negative, it is necessary to construct the screen so that in itself it constitutes a condenser, or an aggregation of condensers, of sufficient electrostatic capacity to dissipate the local charges built up on the front surface of the screen due to the pressure or to the relative movement between the screen and the negative with which it is in contact. Consequently, a conductive layer, viz., a layer comprising conductive material, is added to the screen in juxtaposition to the front surface but separated therefrom by dielectric material. The various layers commonly employed in the more recent forms of intensifying screens themselves are of material having reasonably good dielectric properties. It is feasible to provide a conductive layer at various stratum levels in the screen structure either as a discrete conductive layer interposed for the purpose, or as a layer which is made partially conductive by introducing conductive material into a layer also employed for another purpose. Several alternative constructions are therefore possible to provide the anti-static effects in accordance with the invention. By using a suitable metal or non-metallic conductive material of small particle size, mixed with a suitable resin or plastic binder, the layer not only provides the required conductivity but, if applied to the rear surface of the supporting sheet 4, tends to seal it against moisture, thus stabilizing the product as to dimensions and anti-static qualities. For this reason, it is preferable that the edges of the backing material, especially if it is of a fibrous nature, be coated also.

We have found that, in general, material having a certain degree of conductivity is required to produce the necessary effective electrostatic capacity. However, since the absorption of X-rays increases with increased density of such materials, there is an optimum relationship between the quantity of metal and its physical form required to provide sufficient conductivity with minimum, or at least tolerable, X-ray absorption. In employing aluminum, which we presently prefer, it appears that a given weight in flake form, for example, provides at least as effective anti-static qualities as does the same weight of aluminum employed in the form of thin foil.

The aluminum layer 5 shown in the screen structure of Fig. 1 preferably is formed as follows: Aluminum flake, of which approximately 98% passes through a 325 mesh screen, is dispersed in a resin binder dissolved in methyl ethyl ketone. An example is as follows:

	Parts by weight
Methyl ethyl ketone	70.0
Vinyl chloride-acetate copolymer	30.0
Aluminum flake	6.0

The aluminum flake is stirred into a binder solution composed of the vinyl chloride-acetate copolymer dissolved in the methyl ethyl ketone. A proportion of aluminum of the mentioned particle size in the range of between approximately 16% and 17% of the total solids appears to provide the most effective anti-static qualities. The dry film thickness of the mentioned coating may, with satisfactory results, vary between 0.0001 inch and 0.002 inch, a coating of 0.0013 inch having been determined to be a satisfactory mean. The linear conductivity is low in such a coating, but the static-reducing effect according to this invention appears not to depend substantially on linear conductivity because the static potentials comprise localized charges which can be dissipated by localized capacitive effects contributed by individual conductive particles, or by small groups thereof, suitably separated by dielectric material. As above stated, this coating also provides excellent protection against moisture absorption by the backing material and incidentally enhances the appearance of the product.

Other resins which may be used as binding materials for the conductive layer include cellulose esters and ethers, acrylic and methacrylic polymers, and other organic soluble thermo-plastic or thermo-setting resins, if capable of furnishing suitable film-forming properties which are compatible, under the conditions of application with the materials employed in the adjacent layers. Additional binding materials which can be employed for the purpose, although probably not so desirable, include methyl cellulose, hydroxy methyl cellulose, polyvinyl alcohol, alcohol-soluble and water-soluble resins and gums, if capable of furnishing suitable film-forming properties and which can be rendered insoluble in water by special treatment. It is undesirable in screens of the nature herein described to employ substances which in their final condition are hygroscopic.

The proportion of aluminum, or other metal, or non-metal, powder or flake which will be required to provide the optimum effect will vary to some degree in accordance with the particular binding material employed and to the treatment which it must be given in the course of the fabrication of the conducting layer. However, this proportion can readily be ascertained by a worker in the art once he has made a selection of the specific materials to be used. Likewise it is unnecessary here to specify the exact solvent to be employed with any selected binder because satisfactory solvents for the various binders are well known in the organic chemistry art.

The electrically conductive material may be any of a variety of substances, including metals and non-metals such as carbon and silicon. Most, if not all of these, are likely to be more expensive than aluminum, and their characteristics are, for the most part, not useful for the purpose as are those of aluminum. However, other metals including iron, nickel, copper, silver, tin, lead and

bismuth, can be used in back screens, viz., behind the X-ray negative. Carbon is less dense and absorbs X-rays less. If the electrically conductive layer is positioned so that X-rays must pass through it in order to penetrate and expose the photographic emulsion on the negative, as in front screens, then it is preferable to use a stable metal of low density, such as aluminum. Satisfactory X-ray transmission can be taken to be that which produces an exposed emulsion density within 2% of the control density. However, the X-ray absorption is immaterial if the conductive metal is placed on the back of the screen, as in Fig. 1, and this screen, in turn, is disposed on the far side of the negative away from the X-ray source, as above mentioned.

The embodiment illustrated in Fig. 2 differs from that of Fig. 1 in two respects. First, an aluminized layer or coating 6 is interposed between the back sheet 4 and the pigmented reflecting layer 3, and second, the rear surface of the backing sheet is coated with a layer 7 which may comprise any desired moisture-resistant resin, but it may be thicker than layer 1. The object of this layer 7 is, as before, to seal the paper or cardboard or other backing material, if necessary, against the absorption of moisture or other substances. If desired, the aluminized layer of Fig. 1 can also be employed on the rear surface instead of the resinous layer 7.

The interposition of an aluminized layer 6 between layers 3 and 4, as in Fig. 2, is satisfactory in its anti-static effects, especially if either the pigmented layer 3 or the fluorescent layer 2, has good dielectric properties. This layer may be formed of any of the materials or combinations of materials above described in connection with conductive layers.

The screen structure of Fig. 3 differs from those of Figs. 1 and 2 in two novel respects. Instead of employing a pigmented layer such as layer 3 in Figs. 1 and 2, the pigmented reflecting layer 8 in this embodiment is made conductive by the addition of aluminum particles. It appears to make little difference whether the particles are of flake or granular form, if of the same preferred particle size, although the flake is usually less expensive. The results of tests indicate that the addition of the aluminum to the pigmented layer, if in the same quantity as above mentioned, provides substantially the same anti-static qualities in the arrangement of Fig. 3 as it does in the arrangement of Fig. 2. However, the specular light-reflecting properties of the layer 8 are somewhat decreased by the addition of the aluminum, and for that reason a light-reflecting layer without the metal particles is preferred, if maximum light output be required. Nevertheless, the structure of Fig. 3 is useful and eliminates the additional layer in the embodiment of Fig. 2. In the structure of Fig. 3 the rear surface of the backing sheet 4 is covered with a thin layer 9 of aluminum as illustrated. Foil of a thickness of 0.002 inch cemented to the backing sheet 4 is suitable for the purpose, although, as above stated, it is more readily damaged than is a coating of aluminum flake in a binder, such as 5 in Fig. 1.

The screen structure illustrated in Fig. 4 is similar to that of Fig. 3 except that the conductive foil on the rear surface of backing sheet 4 here comprises a resinous layer containing aluminum particles as described in connection with Fig. 1. Although the light-reflecting properties of layer 8 are, as above mentioned in connection with Fig. 3, somewhat decreased by the addition of the aluminum particles, the anti-static properties of the structure are at least as good as those of any of the preceding structures because the dielectric backing sheet has a conductive layer on each side of it. The improved charge-absorbing characteristics of this structure are believed to result from the presence of a conductive layer 8 below the dielectric layers 1 and 2 and of another conductive layer 5 below the dielectric layer 4.

The intensifying screen illustrated in Fig. 5 is different

from all of the others in the respect that aluminum (or other conductive) particles are dispersed in all of the layers, except the backing sheet. Here, the rear surface of the backing sheet 4 is coated with an aluminized layer 5, as in Fig. 1, and the front surface of the backing sheet 4 is coated with a mixture of titanium dioxide and aluminum particles in a suitable binder forming a coating 8 which is the same as that illustrated in Fig. 3. Additionally, in the present embodiment, the fluorescent layer 11 and the protective coating 12 both contain conductive particles, but preferably in lesser quality than in the other layers. The electrical effect of this construction is that the three top layers 8, 11 and 12 act as a single conductor or electrode, and the layer 5 on the rear of dielectric sheet 4 acts as the second conductor, or electrode, of the condenser. Electrically this construction is effective in eliminating the undesirable effects of static, but the addition of conductive particles in the layers 11 and 12 reduces the transmission of light. This embodiment illustrates the fact that substantially any one or a combination of the layers above or below the backing sheet can be made conductive, if separated by a dielectric layer, in order to dissipate the deleterious static charges, as above explained. It is also to be understood that metallic foil, especially if of low X-ray absorption, can be substituted for the conductive particles in any discretely conductive layer.

We claim:

1. An X-ray intensifying screen comprising a backing sheet of cardboard, a moisture resistant and electrically conductive coating of aluminum particles in a resin binder on the back and edges of said sheet, a light-reflecting layer containing titanium dioxide on the front of said sheet, a fluorescent layer on the reflecting layer, and a smooth, thin, transparent, protective dielectric coating film over the fluorescent layer, whereby to minimize static discharges when the surface of said protective dielectric coating film is pressed against a radiographic film and subsequently removed therefrom.

2. An X-ray intensifying screen comprising in the order named: a translucent, moisture-resistant protective coating film of dielectric material, a fluorescent layer, a dielectric backing sheet and a moisture resistant and electrically conductive coating comprising metallic aluminum particles in a binder on the rear surface of said backing sheet, whereby to minimize static discharges when the surface of said protective coating film is pressed against a radiographic film and subsequently removed therefrom.

3. An X-ray intensifying screen comprising a backing sheet having dielectric properties, a coating between .0001 and .002 inch thick on the rear surface of said sheet comprising aluminum particles substantially of 325 mesh in a binder of vinyl chloride-acetate copolymer in proportion of the order of 1:5 by weight, a pigmented layer on the front of said sheet comprising titanium dioxide, a fluorescent layer on said pigmented layer comprising a phosphor material in a resin binder, and a protective film comprising transparent material having dielectric properties covering said fluorescent layer, whereby to minimize static discharges when the surface of said protective film is pressed against a radiographic film and subsequently removed therefrom.

4. An X-ray intensifying screen comprising a backing sheet of dielectric material, a moisture-resistant coating layer on one side of said sheet, a pigmented light-reflecting layer over the other side of said sheet, a fluorescent layer on said pigmented layer, and a static-forming translucent protective layer including a dielectric resinous material on said fluorescent layer, said moisture-resistant coating layer being characterized in that it contains metallic particles in quantity sufficient to impart electrical conductivity thereto such as to minimize localized static discharges when the face of said screen which bears said

protective layer is pressed against a photographic negative and subsequently removed therefrom.

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UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 2,904,689 September 15, 1959

Frank J. Masi et al.

It is hereby certified that error appears in the printed specification of the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 1, lines 16 and 17, for "photositive" read -- photosensitive --; column 5, line 17, for "back" read -- backing --; column 6, line 11, for "quality" read -- quantity --.

Signed and sealed this 1st day of March 1960.

(SEAL)

Attest:

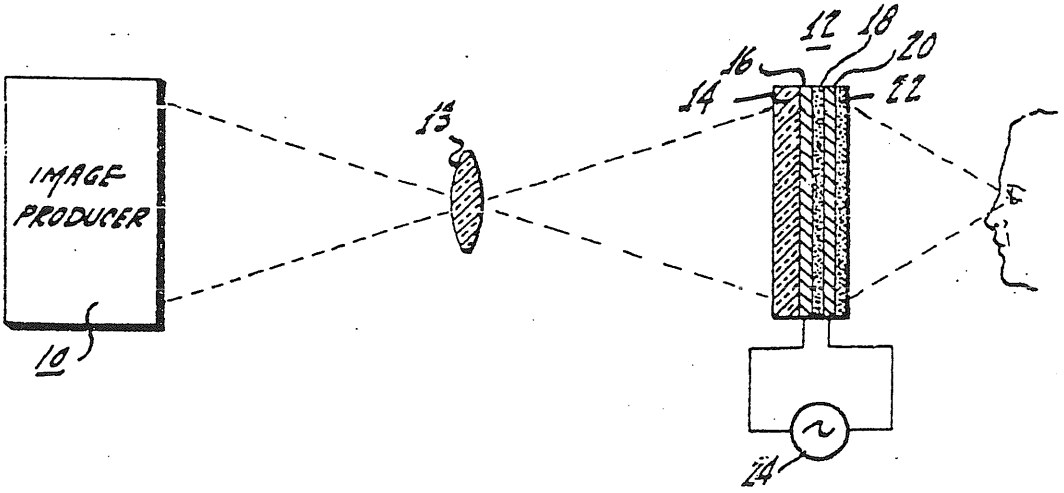
KARL H. AXLINE
Attesting Officer

ROBERT C. WATSON
Commissioner of Patents

Nov. 13, 1962 R. D. KELL 3,064,134

DISPLAY DEVICE

Filed Nov. 15, 1960



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United States Patent Office 3,064,134 Patented Nov. 13, 1962

3,064,134

DISPLAY DEVICE

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Filed Nov. 15, 1960, Ser. No. 69,466
3 Claims. (Cl. 250—213)

This invention relates to display devices. In particular, this invention relates to an image reproducer type display device.

In most of the known display devices, the device itself must generate both the brightness and the scene information. In certain instances, this is extremely undesirable. For example, when viewing a P.P.I. radar display while in high ambient illumination, such as in an aircraft, the amount of brightness that must be developed by the display device before the signal can be properly seen is large. When this high brightness level is reached, the device must further produce the signal information as a contrast to the brightness. Such procedure necessarily requires the use of large power supplies and other undesirable conditions.

It is therefore an object of this invention to provide a new and improved display device.

It is a further object of this invention to provide a novel display device that can readily be viewed even when the ambient light level is high.

These and other objects are accomplished in accordance with this invention by providing a display device that includes a thermo-chromatic material positioned in a heat exchange relationship with a thermal-image producing means. By coupling an image of a scene to be reproduced onto the thermal-image producing means, and by coupling the thermal-image to the thermo-chromatic material, a visible image is produced on the thermo-chromatic material which is proportional to the intensity of the light from the scene. The image produced by the thermo-chromatic material is of two colors, one for the areas energized by the heat and a different color for that of the areas which are not so energized. Thus, only the signal information is produced by the viewing device and the non-signal brightness level is automatically provided by the color of the thermo-chromatic material in its unexcited regions.

The invention will be more clearly understood by reference to the accompanying single sheet of drawings wherein:

The single FIGURE is a schematic representation of one form of this invention.

Referring now to the drawing, there is shown an image producer 10. The image producer 10 may be any of the many known image producing devices such as a cathode ray tube, a display storage tube, an electroluminescent panel or other similar image producing device. Also, the image may be caused by the light directly from a scene to be reproduced. The image may be in the form of a visible light, infra-red radiation, X-rays or other known radiations. The optical image from the image producer 10 is focused onto a display device 12 by means of any suitable imaging lens system represented by a lens 13. The optical image may however, be applied directly to the display device 12. For example, the face of a display cathode ray tube may be placed in direct contact with the display device 12.

The display device 12 comprises a support member 14 which is made of any material that is transparent to the image from the image producer 10. As an example, when the image from the producer 10 is a visible image, the support member 14 may be made of glass or of a light transparent plastic, for example Mylar. If the image from the image producer 10 is infra-red, a support member of mica may be used.

On the support member 14 there is provided an electrical conductive coating 16. The conductive coating 16 is also transparent to the image from the image producer 10. As an example, a transparent conductive coating of tin oxide may be used.

On the transparent conductive coating 16 there is provided a layer of material 18 which generates heat when it is exposed to an image. One example of a material which may be used for the heat generator 18 is a photoconductor. The heat generating layer 18 is selected for its property of developing heat in response to an input image. The photoconductor, with a potential difference applied thereacross, develops heat, because of current flow through the photoconductor when the photoconductor is exposed to radiation. The heat generation in a photoconductor occurs only in the areas in which the current flows and thus is confined to the illuminated elemental areas. The amount of heat generated is proportional to the amount of resistance change which, in turn, is proportional to the amount of light from the screen. One of the known photoconductive materials which may be deposited in large areas is powdered cadmium sulfide supported in a dielectric binding material such as ethyl cellulose or polystryrene. The photoconductive material and binder may be approximately one to ten mils thick. Other photoconductive materials, such as cadmium selenide for example, may also be used.

On the heat generating layer 18 there is provided a thin electrical conductor 20 which may be either transparent, e.g. tin chloride, or opaque, e.g. aluminum. The electrical conductor 20 should be thin, e.g. approximately 1 mil, so that the thermal image developed will not tend to spread laterally which would result in loss of image resolution.

On the electrical conductor 20 there is provided a layer of thermo-chromatic material 22. One example of thermo-chromatic material is copper mercuric iodide in a suitable binder such as glyptol or varnish. The thermo-chromatic material 22 may be sprayed or brushed on and may be approximately 0.1 mil thick.

During operation of the device 12, a potential difference is applied between the conductors 16 and 20 by means of electrical power source 24. When an image from the image producer 10 strikes the heat generating means 18, the layer 18 produces a heat image that corresponds to the optical image from the image producer 10. In the particular example given above, the heat image is caused by electrical current flow through the photoconductor proportional to the illumination in the various areas of the optical image. The heat image from the heat generating element 18 is coupled by heat conduction, through the conductive layer 20 to the thermo-chromatic material 22 so that the thermo-chromatic material changes color because of the change in temperature. As an example, a copper mercuric iodide layer will change from bright-red in color, when the material is below approximately 70° C., to jet black in color when the temperature is about 75° C. or greater. Such changes in color are reversible. A potential difference of 50 volts A.C., for example, between the electrodes 16 and 20 provides sufficient current flow to generate sufficient heat to raise the temperature of the thermo-chromatic material the required 5° in the particular example given. Another example of a thermo-chromatic material is mercuric iodide which changes from a yellow color to red at about 126° C.

In the areas of the scene to be reproduced, which are not excited by light, there is no current flow through the photoconductor 18. In the illuminated areas there is a current flow, which is proportional to the amount of illumination striking the photoconductor 18 resulting in

a localized thermal-image. The localized heating produces a negative visible image of the original optical image that has been applied to the photoconductor. Thus, light may be projected through photographic negatives and onto the photoconductor material 18 and positive pictures may then be viewed on the thermo-chromatic material 22. The maximum speed of response of the device is believed to be limited primarily by the lag which occurs in the photoconductor. Thus, under proper lighting conditions, a response time of 1/30 of a second can be obtained.

It should be understood that, when the image producer 10 is a cathode ray tube, the face plate is preferably thin so that the image will not be diffused as it passes through the glass face plate. One example of a thin window tube may be found in an article entitled, "Thin-Window Cathode Ray Tube for High Speed Printing with Electrofax," by R. C. Olden, which appeared in the RCA Review of September 1957.

Thus, applicant's invention is particularly useful in instances wherein the viewing is to be done under high ambient lighting conditions. Also, this invention is particularly useful when a thin light weight display device is desired.

What is claimed is:

1 An image display device comprising a glass support member, a transparent electrical conductive coating on said support member, a layer of powdered cadmium sulfide on said coating, a conductor on said layer of cadmium sulfide, and a layer of copper mercuric iodide on said conductor.

2. An image display device comprising a support member, a light transparent electrical conductive coating on said support member, a layer of powdered cadmium selenide on said coating, a conductor on said layer of cadmium selenide, a layer of copper mercuric iodide on said conductor and in heat receiving relationship with said layer of cadmium selenide.

3. An image display device comprising a transparent support member, a light transparent electrical conductive coating on said support member, a layer of a photoconductive powder and binder on said conductive coating, a conductor on said layer, and a layer of mercuric iodide on said conductor.

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AERIAL PROSPECTING

Filed June 4, 1954 3 Sheets-Sheet 1

Fig. 1.

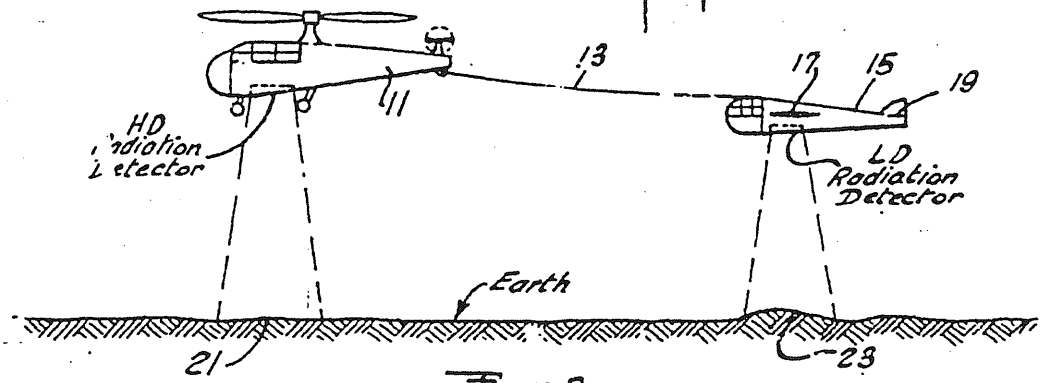


Fig. 2.

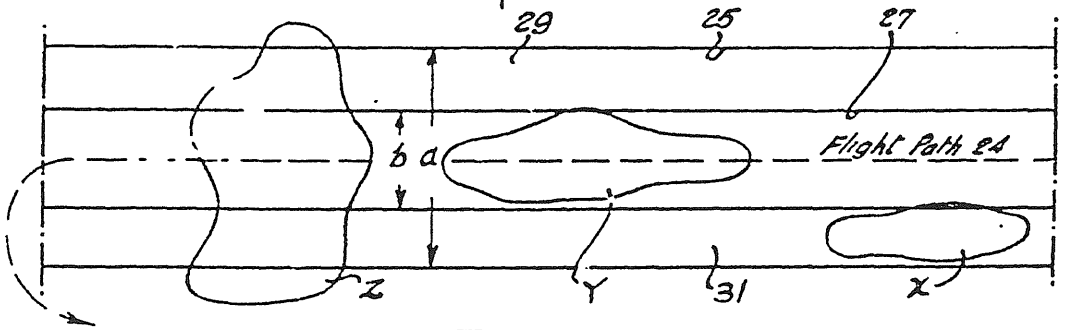


Fig. 3.

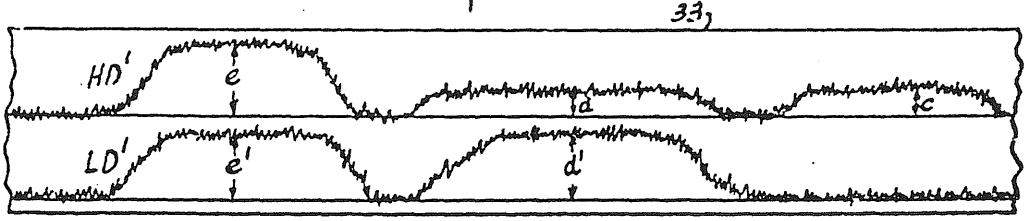
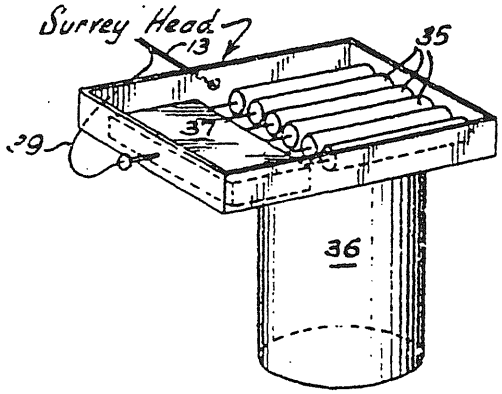


Fig. 4.



Sept. 15, 1959 R. P. MULLIGAN 2,904,691

AERIAL PROSPECTING

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Fig. 5.

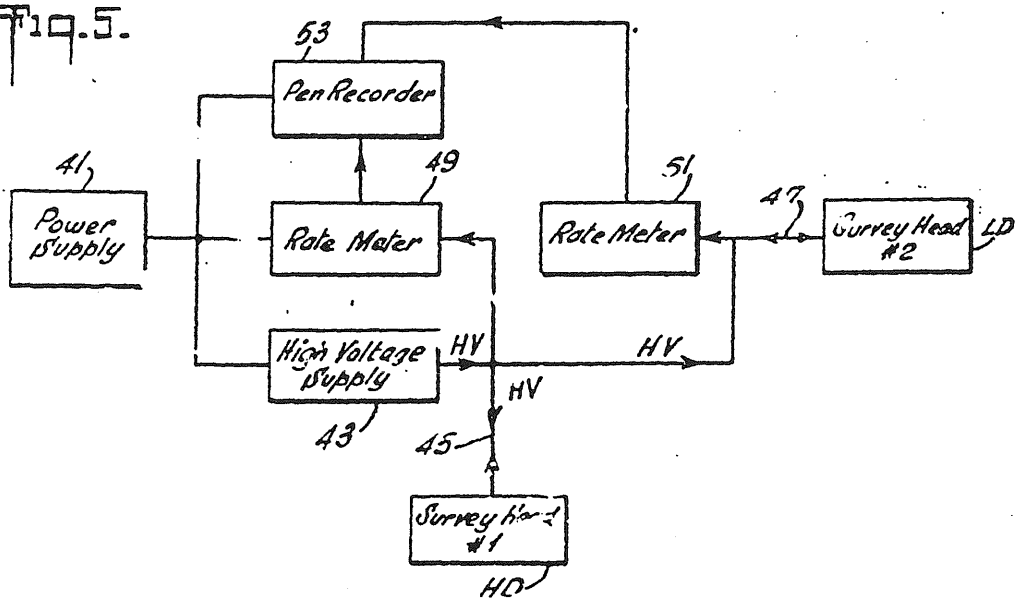


Fig. 6.

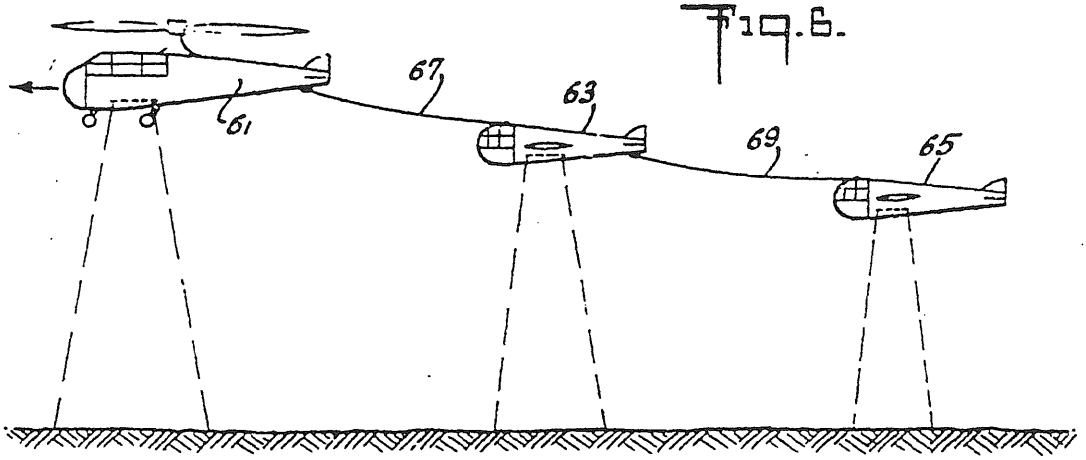
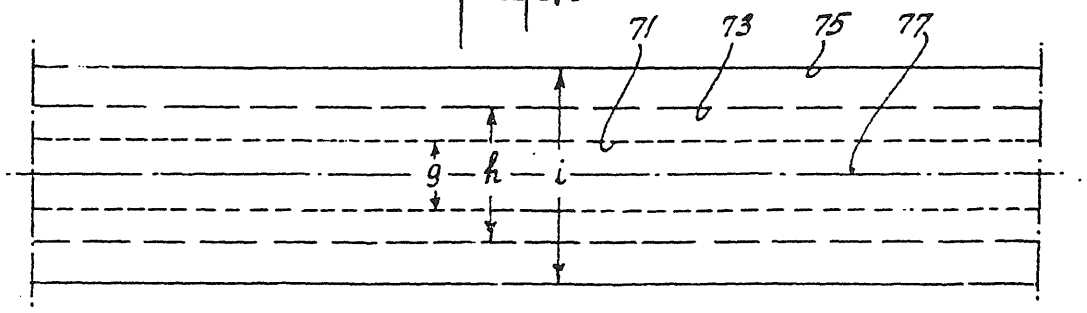


Fig. 7.



July 6, 1965 L. REIFFEL 3,193,683

MEASURING SYSTEM USING THE RESONANT ABSORPTION OF GAMMA RAYS

Filed May 23, 1960 2 Sheets-Sheet 1

Fig-1

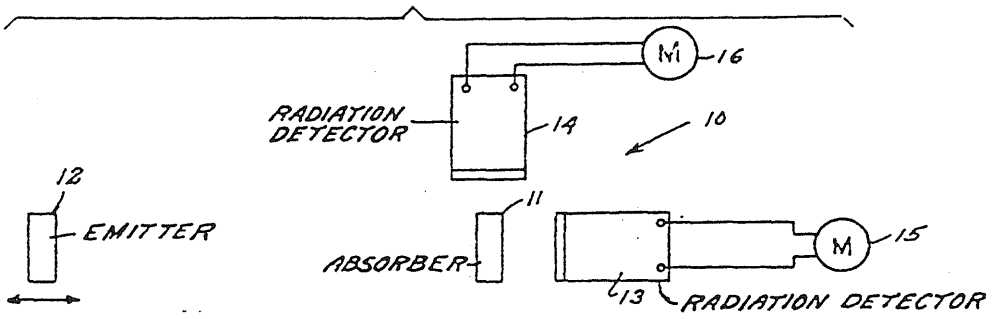


Fig-2

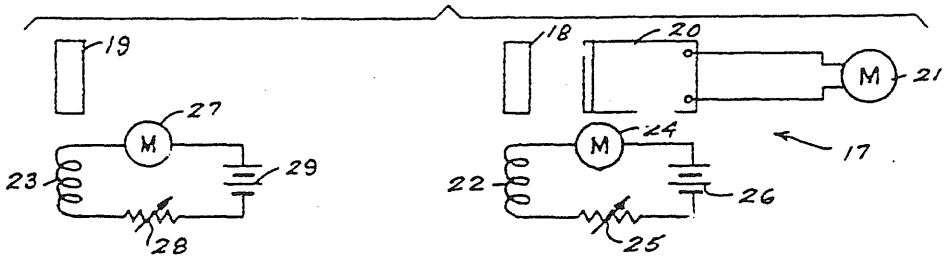


Fig-3

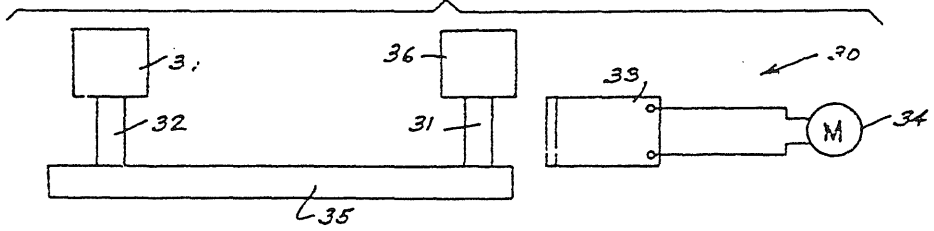
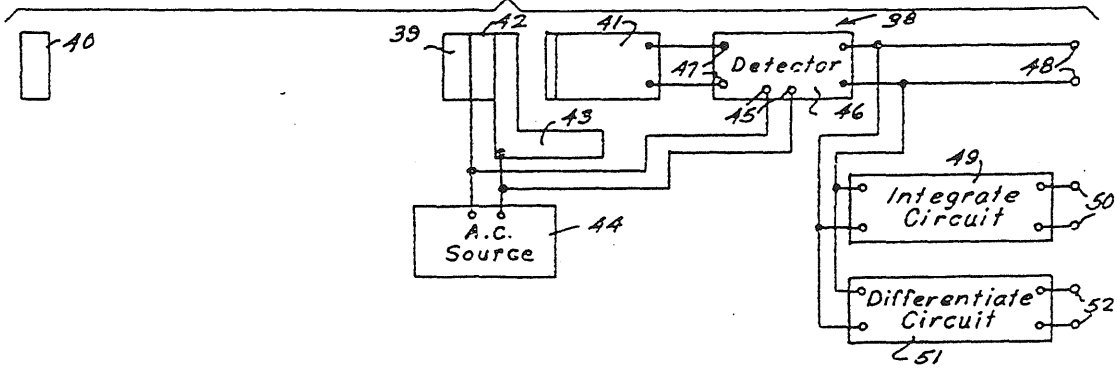


Fig-4



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MEASURING SYSTEM USING THE RESONANT ABSORPTION OF GAMMA RAYS

Filed May 23, 1960 2 Sheets-Sheet 2

Fig. 5

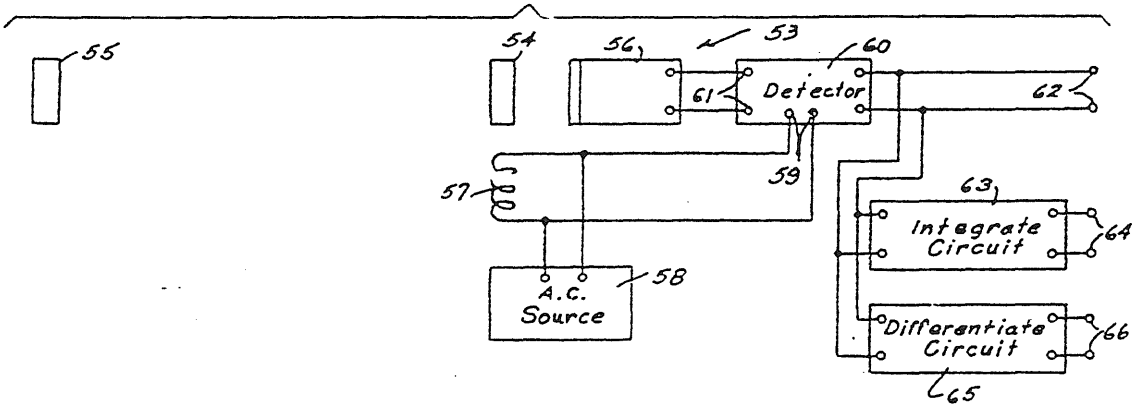


Fig. 6

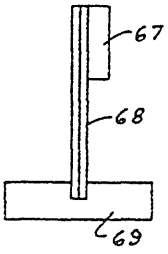


Fig. 7

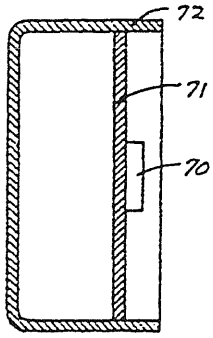
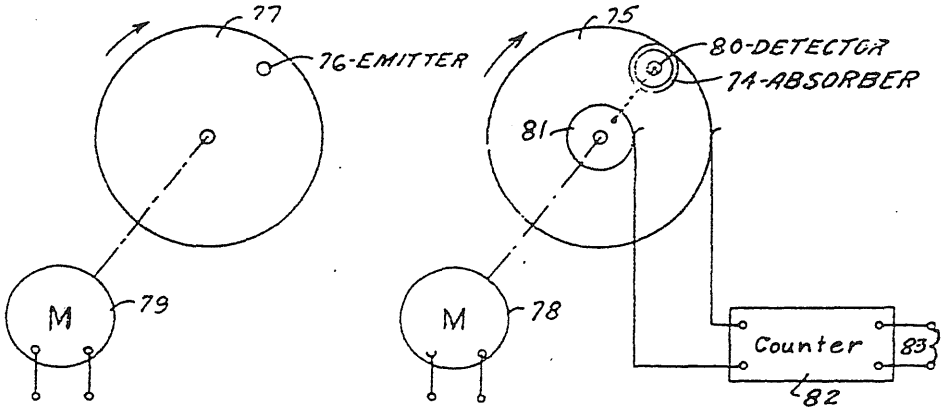


Fig. 8



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United States Patent Office

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3,193,683
MEASURING SYSTEM USING THE RESONANT ABSORPTION OF GAMMA RAYS

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Filed May 23, 1960, Ser. No. 30,983
18 Claims. (Cl. 250—106)

This invention relates to a measurement system using gamma rays, operative to perform measurements of certain variables with high accuracy and in conditions under which such measurements could not heretofore be performed.

Prior art systems for measuring many variables have had a number of limitations. In some cases, the transducer device used for sensing the variable has created difficulties. In other cases, a severe limitation has arisen in the transmission of information to a measuring instrument from a point at which the variable is sensed. For example, in the measurement of vibrations, conventional transducers create a load on the vibrating member, preventing accurate measurement, and in addition are quite cumbersome. Light, doppler sonic methods and other vibration measuring methods have had limitations with respect to obtaining an unobstructed, uniform path for transmission of information. In addition, the measurement of small variations has been impossible or extremely difficult. In other systems, for example in measurement of temperature, environmental conditions have created severe limitations.

This invention was evolved with the object of providing a system for measuring certain variables with a high degree of accuracy and in conditions under which prior art systems are unsatisfactory.

This invention involves the use of gamma rays which are electromagnetic waves identical in nature to X-rays, but are of higher energy and are more penetrating. Gamma rays are emitted by a reaction that takes place within the nuclei of atoms of various radio-active materials. Such atoms comprise a nucleus surrounded by electrons which travel in orbital shells or rings at various distances from the nucleus. The nucleus comprises nucleons which may be thought of crudely as travelling in orbital rings having diameters much smaller than those of the electron rings. Characteristic X-rays are emitted in response to the removal of an electron from an inner electron ring, followed by the transfer of an electron from an outer ring to the inner ring, with the emanation of electromagnetic wave energy of a certain energy or frequency (energy and frequency being proportional). In a somewhat similar way, gamma rays are emitted in response to rearrangement of the nuclear structure in which a nucleon may be crudely considered to move an outer ring to an inner ring, with the emanation of electromagnetic wave energy of a certain energy or frequency. In general, the energy or frequency of gamma rays is much higher than the energy or frequency of characteristic X-rays.

The packet of gamma radiations sent out as a result of a single transition is termed a "photon." As to a given atom, the transition occurs at an unpredictable moment. However, in a given sample of radio-active material, the overall rate is predictable and it decreases in a predictable fashion as the energy of the sample decreases.

In general, the absorption of gamma rays by a given material is proportional to the thickness and density of the material. However, the absorption of gamma rays may be sharply increased under certain very critical resonant absorption conditions, which are involved in this invention.

Resonant absorption occurs when the energy or frequency of the gamma rays impinged on a material is within a certain very narrow frequency range such as to cause rearrangement of the intra-nucleus structure of atoms within the material. Resonant absorption does not ordinarily occur because of a doppler effect produced by relative movement of the emitting and absorbing nuclei, sufficient to shift the effective energy or frequency out of the required very narrow range. Even with the emitter and absorber stationary, such relative movement occurs due to a recoil effect on the emitting nucleus, resulting in a lowering of the energy or frequency of the emitted rays and a similar recoil effected on the absorbing nuclei, necessitating a higher frequency or energy to produce resonant absorption.

Although resonant absorption does not ordinarily occur, it will occur under certain critical conditions with certain materials in which the nuclei are bound by atomic forces in such a manner as to prevent or minimize the recoil effects. For example, certain crystalline forms of the iron isotope of mass 57 (Fe^{57}) may be used. Fe^{57} is produced by the decay of Co^{57} and emits gamma rays with a comparatively low energy (14,000 electron volts).

Even with proper materials, it is found that resonant absorption will occur only if other conditions are within narrow limits. The production of the effect is found to be quite sensitive to relative movement between the emitter and absorber, which produces a doppler effect and a change in frequency. It is also affected by magnetic fields in the vicinity of the emitter or absorber. In addition, the application of stress to the emitter and absorber may affect production of the effect. As a result, it is possible to measure such conditions through the use of the resonant absorption phenomenon.

According to this invention, a measuring system is provided which includes a resonant absorber of such material as to resonantly absorb gamma rays within a very narrow frequency range. A radio-active emitter is effective through intra-nucleus reaction to emit and transmit to the absorber gamma rays having a certain effective frequency at the absorber, and a radiation detector is provided for measuring the absorption of gamma rays by the resonant absorber. The difference between the effective frequency and the mid-frequency of the response range is affected by the relative magnetic field strengths at the emitter and absorber, the relative speed of movement thereof, and relative stress conditions. Temperature also has an effect which may or may not be applicable, depending upon the type of material. With three of such parameters being substantially constant, the fourth may be measured. For example, with the relative temperatures, the relative magnetic field strengths and the relative stress conditions being substantially constant, the system can detect changes in the relative speed of movement of the emitter and absorber. In a similar way, the system can measure changes in relative magnetic fields and in stress conditions.

With this system, it is possible to obtain an extremely high degree of accuracy, under conditions where prior art systems would not be suitable. For example, it is possible to accurately measure velocities in a range from 1 centimeter per second down to 10 microns per second, or even less. The emitter can be extremely compact, and can be disposed in comparatively inaccessible locations, at a considerable distance from the absorber and detector. The gamma rays readily penetrate walls, and have considerable range. They are not affected by changes in the medium between the emitter and absorber such as winds or changes in refractive index which would affect sonic systems, for example.

The possible fields of use of the system are endless. It can be used in any application where it is desired to measure velocity, or a quantity functionally related to velocity, such as distance, acceleration, or any other velocity function. Thus it can be used in measuring preces-

sion of gyros, in seismograph work, in machine tool applications, in the measurement of vibrations both continuous and non-continuous, and in acoustics to measure amplitude, frequency, etc.

It can also be used in the direct measurement of temperature, or in the measurement of temperature indirectly, by using a bimetal element to convert temperature changes to movement. Likewise it can be used in the measurement of pressure, and in the measurement of strain.

The system can be used in the direct measurement of stress within the emitter and/or absorber, and can also be used in the indirect measurement of stress, by first converting stress into strain or movement and measuring the movement.

The system has important advantages in the measurement of magnetic fields, in that the emitter can be extremely compact and can be located at a point remote from the absorber and detector.

An important specific feature of the invention is in the provision of means including a phase-sensitive detector for determining the direction of change of a variable being measured.

This invention contemplates other objects, features and advantages which will become more fully apparent from the following detailed disclosure taken in conjunction with the accompanying drawings which illustrate preferred embodiments and in which:

FIGURE 1 is a view illustrating diagrammatically a system constructed according to the principles of this invention, usable for measuring velocity;

FIGURE 2 is a view illustrating diagrammatically a system usable for measuring relative magnetic fields;

FIGURE 3 is a view illustrating diagrammatically a system for measuring relative stress conditions;

FIGURE 4 is a view illustrating diagrammatically a system for automatically obtaining an indication of both the direction and magnitude of a change of a variable, using vibration means in conjunction with a phase detector;

FIGURE 5 is a view illustrating diagrammatically another system for automatically obtaining an indication of both the direction and magnitude of change of a variable, using an alternating magnetic field in conjunction with a phase detector;

FIGURE 6 is a view illustrating diagrammatically the support of a member on a bimetal element, permitting measurement of temperature variations;

FIGURE 7 is a view illustrating diagrammatically the support of a member on a diaphragm, usable in measuring pressure and in acoustics; and

FIGURE 8 is a view illustrating diagrammatically a system for measuring variations in relative speeds of rotation.

Referring to FIGURE 1, reference numeral 10 designates a system usable for measuring velocity. The system 10 comprises a resonant absorber 11, a radio-active emitter 12, and radiation detectors 13 and 14 for measuring the absorption of gamma rays by the resonant absorber 11. As illustrated, the outputs of detectors 13 and 14 are connected to meters 15 and 16.

The absorber 11 and the emitter 12 are of such materials that the nuclei thereof are bound into a crystal lattice such that a useful fraction of the nuclear disintegration thereof will lead to emission or absorption at well defined resonant energies or frequencies. For example, the absorber 11 may be of a crystalline form of the iron isotope of mass 57 (Fe^{57}) and the emitter 12 may be of the same isotope, activated to emit gamma rays at an energy of about 14,000 electron volts.

In operation, the absorber 11 resonantly absorbs gamma rays within a certain narrow frequency range, and the radio-active emitter 12 is effective to transmit to the absorber 11 gamma rays having a certain effective frequency at the absorber 11. The difference between said effective frequency and the mid-frequency of said narrow range is

affected by the relative temperatures and relative magnetic field strengths at the emitter and absorber, the relative speed of movement of the emitter and absorber and relative stress conditions within the emitter and absorber. It may be assumed that the relative temperatures are constant, that the magnetic fields in the regions of the emitter 12 and the absorber 11 are zero or constant, that the members 11, 12 are subjected to zero or constant internal stresses and that they are stationary relative to each other. Under such conditions, and with the proper materials, the effective frequency of the gamma rays at the absorber 11 will be equal to the mid-frequency of the resonant absorption range of the absorber 11. There will be a maximum absorption, and the output of the detector 13, as observed on the meter 15, will be at a minimum. The gamma rays absorbed by the absorber 11 are converted in part into a secondary radiation which is detected by the detector 14, the output of which is observed on the meter 16. Thus under the above conditions, the meter 16 will indicate a maximum output.

Suppose now that the emitter 12 is moved slowly at a constant speed toward or away from the absorber 11, the other conditions remaining the same. This will result in an increase in the reading on the meter 15 and a decrease in the reading on the meter 16. Thus velocity may be measured. To ascertain the actual velocity, the absorber 11 may be moved toward or away from the emitter 12 and its velocity of movement adjusted until a resonant condition is again established, as indicated by the meters 15, 16. The velocity of the absorber 11, required to achieve the resonant condition, may be measured by any suitable means. It will of course be appreciated that the velocity of the absorber 11 may be the unknown factor, and the emitter 12 may be moved to establish a resonant condition, and its velocity measured to ascertain the velocity of movement of the absorber 11.

The system 10 may also be used for measuring temperature, if the relative velocity of the members and other conditions are maintained zero or constant.

It will be appreciated that the absorption of gamma rays by the absorber 11 may be measured either by the detector 13, responsive to gamma rays passed through the absorber, or by the detector 14, responsive to secondary radiation or scattering. It is not necessary to use both. In general, the use of the detector 13, responsive to gamma rays passed through the absorber 11, is preferred.

Referring to FIGURE 2, reference numeral 17 generally designates a modified system constructed according to the principles of this invention, used for measuring relative magnetic fields. The system 17 comprises an absorber 18, an emitter 19, and a detector 20 having its output connected to a meter 21. These may be constructed and may operate in generally the same manner as the absorber 11, the emitter 12, the detector 13 and the meter 15 in the arrangement of FIGURE 1. However, the system 17 is designed to measure magnetic fields, rather than motion. For this purpose, field-producing means in the form of a coil 22 is disposed adjacent the absorber 18 and field-producing means in the form of a coil 23 is disposed adjacent the emitter 19. Coil 22 is connected through a meter 24 and a variable resistor 25 to a battery 26. Similarly, coil 23 is connected through a meter 27 and a resistor 28 to a battery 29.

With no current through coils 22, 23 and with the members 18, 19 stationary and subjected to zero or constant internal stress conditions, a resonant condition may exist and the absorption of gamma rays by the absorber 18 may be at a maximum, the output of the detector 20 as observed on the meter 21 being at a minimum. If, however, the magnetic field in the region of one member is changed without changing the field in the region of the other member, the resonant condition may be partly or totally destroyed, to decrease absorption by the absorber 18 and to increase the output of the detector 20. Sup-

pose, for example, that a field is applied to the emitter 19, by decreasing the resistance of resistor 28 to obtain a certain current flow through the coil 23. The output of the detector 20 will then increase, thus indicating a change in the magnetic field. To ascertain the magnitude of the field, the resistance of resistor 25 may be reduced in value until a sufficient field is applied to the absorber 18 to restore the resonant condition, as indicated by minimum reading of the meter 21. The reading on the meter 24 then indicates the field in the region of the emitter 19. It will be appreciated, of course, that the field to be measured need not be applied from the coil 23, but may be the field developed by any source.

The system may also be used in measuring an unknown field existing at the absorber 18, by adjusting resistor 28 to obtain the resonant condition and noting the reading on the meter 27.

In many cases, the direction of the field to be measured will be unknown and in that case, the position of the coil 22, or the coil 23, may be reversed or the battery polarity may be reversed as through a reversing switch. It should also be noted that the orientation of the field to be measured, and the balancing field, may be changed from the orientation as illustrated, as required in a particular measuring operation.

Referring to FIGURE 3, reference numeral 30 designates another modified system, usable in the measurement of internal stress conditions. The system 30 comprises an absorber 31, an emitter 32 and a detector 33 responsive to gamma rays passed from the emitter 32 through the absorber 31, the output of the detector 33 being connected to a meter 34. These elements are operative in the same general manner as the similar elements of the systems 10 and 17 described above.

As diagrammatically illustrated, the absorber 31 and the emitter 32 are disposed on a support 35 and a pair of blocks 36 and 37 press against the absorber 31 and the emitter 32, to develop internal stresses therewithin.

With equal stresses developed within the absorber 31 and the emitter 32, a resonance condition may be established, other conditions being appropriate, so that the output of the detector 33 will be at a minimum, as observed on the meter 34. If the stress condition within the emitter 32 is changed, for example, as by changing the weight of the block 37, an off-resonant condition may be established. The resonant condition may then be reestablished, by changing the stress condition within the absorber 31, as by changing the weight of the block 36. Accordingly, if an unknown stress is developed within either the absorber 31 or the emitter 32, the magnitude of the stress may be determined by applying a known stress to the other member, sufficient to reestablish the resonant condition.

If desired, the member subjected to the unknown stress may be made as a small integral part of a larger member. For example, the emitter might be integrally embedded within a large block to ascertain stress conditions within the interior of the block.

It should be noted that it is possible to measure a change in a parameter affecting either the emitter or the absorber by making a measurable change in a different parameter affecting the other, to reestablish a resonant condition, provided suitable calibration standards are established. For example, the velocity of the emitter may be measured by applying a measurable magnetic field to the absorber, sufficient to reestablish the resonant condition. In general, however, it is preferable that the same parameters be changed. For example, to measure a velocity, it is preferable that a measurable change be made in the absorber velocity, sufficient to reestablish the resonant condition.

Referring now to FIGURE 4, reference numeral 38 generally designates a system for automatically providing an indication of both the magnitude and the direction of a change of a parameter being measured. The system 38 comprises a resonant absorber 39, a gamma ray emitter 40 and a detector 41 for measuring the gamma rays passed from the emitter through the absorber. The absorber 39 is vibrated to move toward and away from the emitter 40. In particular, absorber 39 is supported on one face of a quartz crystal 42 the opposite face of which is secured on a fixed support 43. An A.C. source 44 is coupled to the crystal 42, to apply an alternating voltage between the opposite faces thereof and to cause it to vibrate in the thickness mode and to cause movement of the absorber 39 toward and away from the emitter 40. The crystal 42 may be provided with suitable electrodes on its opposite faces thereof or the absorber 39 and the support 43 may be used as electrodes.

The A.C. source 44 is connected to one pair of input terminals 45 of a phase detector 46 having a second pair of input terminals 47 connected to the output of the radiation detector 41. The output of the phase detector 46 is connected to a pair of output terminals 48 which may be connected to a meter or any desired form of utilization means.

In operation, the absorber 39 is moved toward the emitter 40 during one phase of the A.C. signal applied from the source 44 and is moved away from the emitter during the opposite phase of the A.C. signal. The phase detector 46 produces an output signal proportional to the net difference between the output of the radiation detector 41 during one phase of the A.C. signal and the output of the radiation detector 41 during the opposite phase of the A.C. signal. If the relative positions of the absorber 39 and the emitter 40 are fixed, if the members are subjected to zero or constant magnetic fields, and if the stress conditions therewithin are zero or constant, the output of the radiation detector 41 during one phase of the A.C. signal will be the same as its output during the opposite phase of the A.C. signal, so that no output voltage will be developed at the output terminals 48. If, however, one of the parameters is changed, a signal will be produced having a polarity corresponding to the direction of the change and having a magnitude proportional to the magnitude of the change. For example, if the emitter 40 is moved slowly away from the absorber 39, the output of the radiation detector 41 will be decreased during the phase of the A.C. signal in which the absorber 39 is moved toward the emitter 40. During the opposite phase of the A.C. signal, in which the absorber 39 is moved away from the emitter 40, the output of the radiation detector 41 will be increased. Thus a net output signal will be developed at the terminals 48, having a certain polarity, and having a magnitude proportional to the velocity of movement of the emitter 40. The system can, of course, be used to measure variables other than velocity.

In many applications, it is desirable to perform integration, differentiation or other operations on the output signal. For this purpose, the output of the phase detector 46 is connected to the input of an integrate circuit 49, the output of which is connected to a pair of output terminals 50, and the output of the phase detector 46 is also connected to the input of a differentiate circuit 51 having its output connected to a pair of output terminals 52. If the system is used for measuring movement of the emitter 40, the output of the integrate circuit 49 provides an indication of distance. Similarly, the output of the differentiate circuit 51 provides an indication of acceleration.

It should be noted that integrating and differentiating circuits may be used without using the phase detector arrangement, in cases where it is not necessary that the system be responsive to the direction of the change in the variable being measured. For example, integrating and/or differentiating circuits may be connected to the outputs of radiation detectors 13, 20 and 32 in the systems of FIGURES 1, 2 and 3.

Referring to FIGURE 5, reference numeral 53 generally designates another system which automatically provides

an indication of both the magnitude and direction of change of a parameter being measured. The system 53 comprises a resonant absorber 54, a gamma ray emitter 55 and a detector 56 for measuring gamma rays passed from the emitter 55 through the absorber 54. A field-producing means in the form of a coil 57 is disposed adjacent the absorber 54 and is coupled to an A.C. source 58. Source 58 is also connected to a pair of input terminals 59 of a phase detector 60 having a second pair of input terminals 61 connected to the output of the radiation detector 56. The output of the phase detector 60 is connected to a pair of output terminals 62 and may also be connected to the input of an integrated circuit 63 connected to output terminals 64, and to the input of a differentiate circuit 65 connected to output terminals 66.

The system 53 operates in generally the same manner as the system 38. The phase detector produces an output signal proportional to the net difference between the output of the phase detector 60, during which the coil 57 applies a field in one direction, and the output of the phase detector during the opposite phase of the A.C. signal, during which the coil 57 applies a field of the opposite direction. In this way, an indication is obtained at output terminals 62, indicative of both the magnitude and direction of a change in a variable being measured. The integrate circuit 63 develops at the output terminals 64 a signal proportional to the integrated value of the phase detector output signal over a given length of time. The differentiate circuit 65 develops at the output terminal 66 a signal proportional to the rate of change of the phase detector output signal.

Referring to FIGURE 6, a member 67 is carried on one end of a bimetal strip 68 which is affixed at its other end to a support 69. The member 67 is thus moved relative to the support 69 in response to temperature variations. This movement of the member 67 may be measured by any of the systems described above. For example, the member 67 may be either a resonant absorber or a gamma ray emitter, of a form as described above.

As shown in FIGURE 7, a member 70 is supported on a diaphragm 71, closing the open end of a cup-shaped housing 72. The member 70 is moved in response to changes in pressure on the diaphragm 71. This movement may be measured by any of the systems described above. The member 70 may be either an emitter or a resonant absorber, such as described above. This arrangement may be used in measuring pressure changes, or in acoustic measurements. It will, of course, be appreciated than any variable may be measured by converting it into a movement, a magnetic field change or a stress change, measurable by the systems described above.

Referring to FIGURE 8, reference numeral 73 generally designates a system usable for measuring the relative rotation of a pair of rotating members. In the system 73, a ring-shaped resonant absorber 74 is supported on a wheel 75, the axis of the absorber 74 being parallel to and at a certain distance from the axis of the wheel 75. An emitter 76 is supported in similar fashion on a second wheel 77, rotatable on an axis parallel to that of the axis of wheel 75. The spacing of the emitter 76 from the axis of wheel 77 is the same as the spacing of the axis of absorber 74 from the axis of wheel 75. The wheels 75 and 77 are rotated by suitable means, such as electric motors 78 and 79 as diagrammatically illustrated.

Disposed within the ring-shaped absorber 74 is a detector device 80, one terminal of which is connected to the wheel 75, and the other terminal of which is connected to a slip ring 81, insulated from the wheel 75. The wheel 75 and the slip ring 81 are connected to input terminals of a counter 82 having output terminals 83 which may be connected to any suitable register or utilization means.

In operation, if the wheels 75 and 77 are rotated at precisely the same speed, and with the absorber 74 and emitter 76 in exactly the same relative angular positions, the distance between the emitter 76 and the effective portion of the absorber 74 will always be the same, and a resonant absorption condition may be maintained, the output of the counter 82 being then at a minimum. If however the relative speed should change even slightly, an increased output signal will be developed. The speed of one or the other of the motors 78, 79 may then be adjusted, to reestablish the synchronized movement and obtain the resonant condition. It will be appreciated that the system may be made automatically operative to maintain two members at the same speed, by using a direction and magnitude responsive system such as illustrated in FIGURES 4 and 5. It will be also appreciated that the same principles can be applied in systems in which the movements are other than rotating, for example in systems in which is it desired to maintain two members in synchronized oscillatory movement.

It should be noted that in some cases, and particularly when magnetic fields are applied, there may be more than one narrow frequency range or line at which the resonant absorption may occur. A single resonant absorption line may in effect be split into multiple lines, each with its own direction of polarization of the gamma rays. In such cases, the system may use one particular line or frequency of the split emission pattern and one particular line or frequency of the split absorption pattern, to make the measurement. Accordingly, it should be understood that reference herein and in the claims to use of a narrow frequency range is not to be construed as limited to the use of the main unsplit line or frequency range.

will be understood that modifications and variations may be effected without departing from the spirit and scope of the novel concepts of this invention.

I claim as my invention:

1. In a system for detection of changes in a certain variable, a resonant absorber of such material as to resonantly absorb gamma rays within a certain narrow frequency range, a radio-active emitter effective through intra-nucleus reaction to emit and transmit to said absorber gamma rays having a certain effective frequency at said absorber, and a detector for measuring the absorption of gamma rays by said resonant absorber, the difference between said effective frequency and the mid-frequency of said narrow frequency range being affected by certain parameters including the relative temperatures and relative magnetic field strengths at said emitter and absorber, the relative speeds of movement of said emitter and absorber and relative stress conditions in said emitter and absorber, three of said parameters being substantially constant and said certain variable being a function of the other of said parameters.

2. In a system for measuring a velocity function of one member relative to another member, a resonant absorber carried by one of said members and of such material as to resonantly absorb gamma rays within a certain narrow frequency range, a radio-active emitter carried by the other of said members and effective through intranucleus reaction to emit and transmit to said absorber gamma rays having a certain effective frequency at said absorber, and a detector for measuring the absorption of gamma rays by said resonant absorber, the difference between said effective frequency and the mid-frequency of said narrow frequency range being affected by certain parameters including the relative temperatures and relative magnetic field strengths at said emitter and absorber, the relative speeds of movement of said emitter and absorber and relative stress conditions in said emitter and absorber, said relative temperatures, said relative magnetic field strengths and said relative stress conditions being substantially constant.

3. In a system for measuring the relative magnetic field strengths at two spaced points, a resonant absorber at one of said points of such material as to resonantly absorb gamma rays within a certain narrow frequency range, a radio-active emitter at the other of said points effective

through intra-nucleus reaction to emit and transmit to said absorber gamma rays having a certain effective frequency at said absorber, and a detector for measuring the absorption of gamma rays by said resonant absorber, the difference between said effective frequency and the mid-frequency of said narrow frequency range being affected by certain parameters including the relative temperatures and relative magnetic field strengths at said emitter and absorber, the relative speeds of movement of said emitter and absorber and relative stress conditions in said emitter and absorber, said relative temperatures, said relative stress conditions and the relative positions of said emitter and absorber being substantially constant and fixed.

4. In a system for measuring relative stress conditions, a resonant absorber subjected to stress and of such material as to resonantly absorb gamma rays within a certain narrow frequency range, a radio-active emitter subjected to stress and effective through intra-nucleus reaction to emit and transmit to said absorber gamma rays having a certain effective frequency at said absorber, and a detector for measuring the absorption of gamma rays by said resonant absorber, the difference between said effective frequency and the mid-frequency of said narrow frequency range being affected by certain parameters including the relative temperatures and relative magnetic field strengths and said emitter and absorber, the relative speeds of movement of said emitter and absorber and relative stress conditions in said emitter and absorber, said relative temperatures, said relative magnetic field strengths and said relative speed being substantially constant.

5. In a system for detection of changes in a certain variable, a resonant absorber of such material as to resonantly absorb gamma rays within a certain narrow frequency range, a radio-active emitter effective through intra-nucleus reaction to emit and transmit to said absorber gamma rays having a certain effective frequency at said absorber, a radiation detector for measuring the absorption of gamma rays by said resonant absorber, the difference between said effective frequency and the mid-frequency of said narrow frequency range being affected by certain parameters including the relative temperatures and relative magnetic field strengths at said emitter and absorber, the relative speeds of movement of said emitter and absorber and relative stress conditions in said emitter and absorber, an A.C. signal source, means coupled to said source and arranged to increase one of said parameters during one phase of the A.C. signal and to decrease said one of said parameters during the opposite phase of the A.C. signal, and a phase detector coupled to said A.C. signal source and to the output of said radiation detector and arranged to produce an output signal proportional to the net difference between the output of said radiation detector during one phase of the A.C. signal and the output of said radiation detector during the opposite phase of said A.C. signal.

6. In a system for detection of changes in a certain variable, a resonant absorber of such material as to resonantly absorb gamma rays within a certain narrow frequency range, a radio-active emitter effective through intra-nucleus reaction to emit and transmit to said absorber gamma rays having a certain effective frequency at said absorber, a radiation detector for measuring the absorption of gamma rays by said resonant absorber, the difference between said effective frequency and the mid-frequency of said narrow frequency range being affected by certain parameters including the relative temperatures and relative magnetic field strengths at said emitter and absorber, the relative speed of movement of said emitter and absorber and relative stress conditions in said emitter and absorber, an A.C. signal source, electro-mechanical transducer means coupled to said source and mechanically coupled to said absorber for vibrating said absorber to move said absorber toward said emitter during one phase of the A.C. signal and to move said absorber away from said emitter during the opposite phase of said signal, and a phase-sensitive detector coupled to said A.C. signal source and to the output of said detector and arranged to produce an output signal proportional to the net difference between the output of said radiation detector during one phase of the A.C. signal and the output of said radiation detector during the opposite phase of said A.C. signal.

7. In a system for detection of changes in a certain variable, a resonant absorber of such material as to resonantly absorb gamma rays within a certain narrow frequency range, a radio-active emitter effective through intra-nucleus reaction to emit and transmit to said absorber gamma rays having a certain effective frequency at said sorber, a radiation detector for measuring the absorption of gamma rays by said resonant absorber, the difference between said effective frequency and the mid-frequency of said narrow frequency range being affected by certain parameters including the relative temperatures and relative magnetic field strengths at said emitter and absorber, the relative speeds of movement of said emitter and absorber and relative stress conditions in said emitter and absorber, an A.C. signal source, field-producing means coupled to said source arranged adjacent said absorber to produce a field in one direction during one phase of the A.C. signal and a field in the opposite direction during the opposite phase of the A.C. signal, and a phase detector coupled to said A.C. signal source and to the output of said radiation detector and arranged to produce an output signal proportional to the net difference between the output of said radiation detector during one phase of the A.C. signal and the output of said radiation detector during the opposite phase of said A.C. signal.

8. In a system for detection of changes in a certain variable, a resonant absorber of such material as to resonantly absorb gamma rays within a certain narrow frequency range, a radio-active emitter effective through intra-nucleus reaction to emit and transmit to said absorber gamma rays having a certain effective frequency at said absorber, a radiation detector for measuring the absorption of gamma rays by said resonant absorber, the difference between said effective frequency and the mid-frequency of said narrow frequency range being affected by certain parameters including the relative temperatures and relative magnetic field strengths at said emitter and absorber, the relative speeds of movement of said emitter and absorber, and relative stress conditions in said emitter and absorber, and A.C. signal source, means coupled to said source and arranged to increase one of said parameters during one phase of the A.C. signal and to decrease said one of said parameters during the opposite phase of the A.C. signal, a phase detector coupled to said A.C. signal source and to the output of said radiation detector and arranged to produce an output signal proportional to the net difference between the output of said radiation detector during one phase of the A.C. signal and the output of said radiation detector during the opposite phase of said A.C. signal, and an integrator circuit connected to the output of said phase detector.

9. In a system for detection of changes in a certain variable, a resonant absorber of such material as to resonantly absorb gamma rays within a certain narrow frequency, a radio-active emitter effective through intra-nucleus reaction to emit and transmit to said absorber gamma rays having a certain effective frequency at said absorber, a radiation detector for measuring the absorption of gamma rays by said resonant absorber, the difference between said effective frequency and the mid-frequency of said narrow frequency range being affected by certain parameters including the relative temperatures and relative magnetic field strengths at said emitter and absorber, the relative speeds of movement of said emitter and absorber and relative stress conditions in said emitter and absorber, an A.C. signal source, means coupled to said source and arranged to increase one of said param-

eters during one phase of the A.C. signal and to decrease said one of said parameters during the opposite phase of the A.C. signal, a phase detector coupled to said A.C. signal source and to the output of said radiation detector and arranged to produce an output signal proportional to the net difference between the output of said radiation detector during one phase of the A.C. signal and the output of said radiation detector during the opposite phase of said A.C. signal, and a differentiating circuit connected to the output of said phase detector.

10. In a method of measuring, using a resonant absorber of such material as to resonantly absorb gamma rays within a certain narrow frequency range, a radio-active emitter effective through intra-nucleus reaction to emit and transmit to said absorber gamma rays having a certain effective frequency at said absorber, and a detector for measuring the absorption of gamma rays by said resonant absorber, the difference between said effective frequency and the mid-frequency of said narrow frequency range being affected by certain parameters including the relative temperatures and relative magnetic field strengths at said emitter and absorber, the relative speeds of movement of said emitter and absorber and relative stress conditions in said emitter and absorber, the steps of making a change in one of said parameters to a certain extent in one direction, then making a change in said one of said parameters to the same extent in the reverse direction, and measuring the differences in the detector outputs obtained during said changes.

11. In a method of measuring, using a resonant absorber member of such material as to resonantly absorb gamma rays within a certain narrow frequency range, a radio-active emitter member effective through intra-nucleus reaction to emit and transmit to said absorber gamma rays having a certain effective frequency at said absorber, and a detector for measuring the absorption of gamma rays by said resonant absorber, the difference between said effective frequency and the mid-frequency of said narrow frequency range being affected by certain parameters including the relative temperatures and relative magnetic field strengths at said emitter and absorber members, the relative speeds of movement of said emitter and absorber members, and relative stress conditions in said emitter and absorber members, the steps of moving one of said members toward the other at a certain speed, then moving said one of said members away from the other at a certain speed, and measuring the difference in the detector outputs during said movements.

12. In a method of measuring, using a resonant absorber member of such material as to resonantly absorb gamma rays within a certain narrow frequency range, a radio-active emitter member effective through intra-nucleus reaction to emit and transmit to said absorber gamma rays having a certain effective frequency at said absorber, and a detector for measuring the absorption of gamma rays by said resonant absorber, the difference between said effective frequency and the mid-frequency of said narrow frequency range being affected by certain parameters including the relative temperatures and relative magnetic field strengths at said emitter and absorber members, the relative speeds of movement of said emitter and absorber members, and relative stress conditions in said emitter and absorber members, the steps of effecting a certain change in one direction of the magnetic field applied to one of said members, effecting a certain change in the reverse direction of the magnetic field applied to said one of said members, and measuring the difference in the detector outputs obtained during said changes.

13. In a temperature measuring system, a resonant absorber member of such material as to resonantly absorb gamma rays within a certain narrow frequency range, a radio-active emitter member effective through intra-nucleus reaction to emit and transmit to said absorber member gamma rays having a certain effective frequency at said absorber member, an element supporting one of said members and arranged to move said one of said members in response to temperature changes to change the distance between said members, and a detector for measuring the absorption of gamma rays by said resonant absorber to measure the change in temperature of said element.

14. In a pressure measuring system, a resonant absorber member of such material as to resonantly absorb gamma rays within a certain narrow frequency range, a radio-active emitter member effective through intra-nucleus reaction to emit and transmit to said absorber member gamma rays having a certain effective frequency at said absorber member, means supporting one of said members and arranged to move said one of said members in response to pressure changes to change the distance between said members, and a detector for measuring the absorption of gamma rays by said resonant absorber members to measure changes in said pressure.

15. In a system for measurement of relative movements of a pair of members, a resonant absorber of such material as to resonantly absorb gamma rays within a certain narrow frequency range, a radio-active emitter effective through intra-nucleus reaction to emit and transmit to said absorber gamma rays having a certain effective frequency at said absorber, said absorber being supported on one of said members for cyclic movement in a certain path, said emitter being supported on the other of said members for cyclic movement in a path similar to said certain path, and a detector for measuring the absorption of gamma rays by said resonant absorber to compare the relative movement of said absorber and emitter.

16. In a system for measuring relative rotation of a pair of members a resonant absorber of such material as to resonantly absorb gamma rays within a certain narrow frequency range, a radio-active emitter effective through intra-nucleus reaction to emit and transmit to said absorber gamma rays having a certain effective frequency at said absorber, said absorber being supported on one of said members at a certain distance from the axis of rotation thereof, said emitter being supported on the other of said members at said certain distance from the axis of rotation thereof, and a detector for measuring the absorption of gamma rays by said resonant absorber to compare the relative rotations of said members.

17. In a system for detection of changes in a certain variable, a resonant absorber of such material as to resonantly absorb gamma rays within a certain narrow frequency range, a radio-active emitter effective through intra-nucleus reaction to emit and transmit to said absorber gamma rays having a certain effective frequency at said absorber, a detector for measuring the absorption of gamma rays by said resonant absorber to respond to differences between said effective frequency and the mid-frequency of said narrow frequency range, and means responsive to the output of said detector including a differentiating circuit.

18. In a system for detection of changes in a certain variable, a resonant absorber of such material as to resonantly absorb gamma rays within a certain narrow frequency range, a radio-active emitter effective through intra-nucleus reaction to emit and transmit to said absorber gamma rays having a certain effective frequency at said absorber, a detector for measuring the absorption of gamma rays by said resonant absorber to respond to differences between said effective frequency and the mid-frequency of said narrow frequency range, and means responsive to the output of said detector including an integrating circuit.

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RALPH G. NILSON, *Primary Examiner.*

March 3, 1964 H. R. CHOPE 3,123,714

SPACE COMMUNICATION SYSTEM

Filed July 21, 1961 3 Sheets-Sheet 1

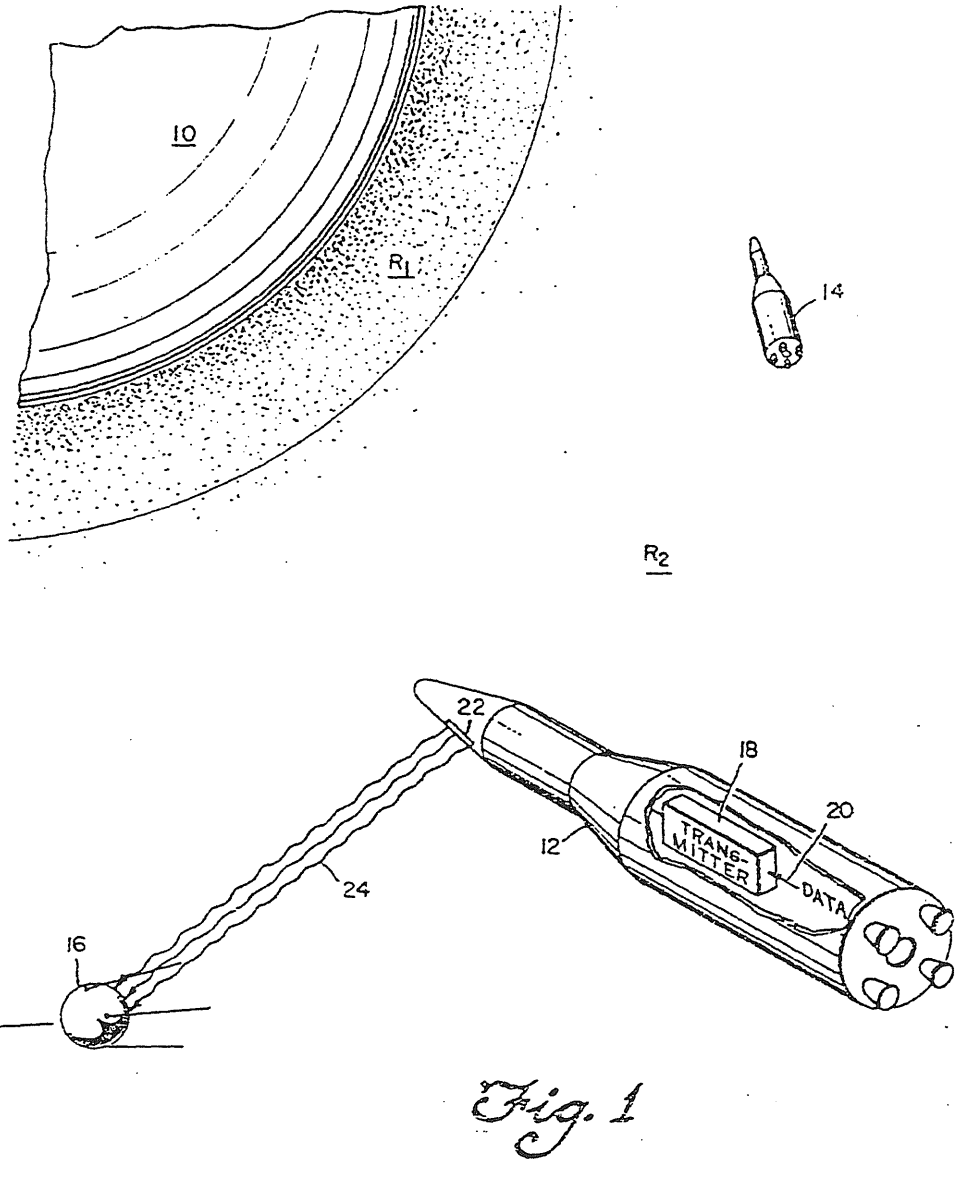

Fig. 1

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SPACE COMMUNICATION SYSTEM

Filed July 21, 1961 3 Sheets-Sheet 2

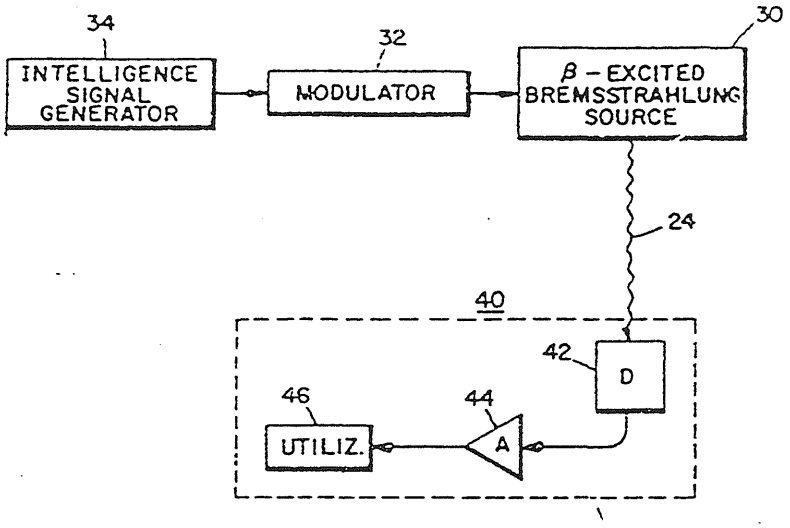

Fig. 2

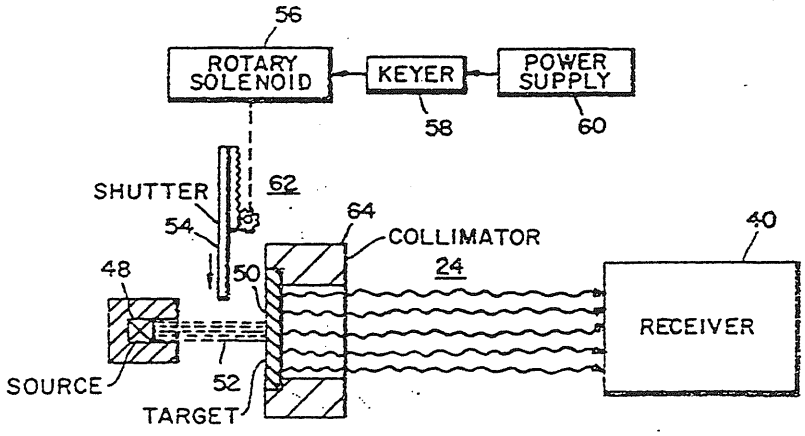

Fig. 3

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SPACE COMMUNICATION SYSTEM

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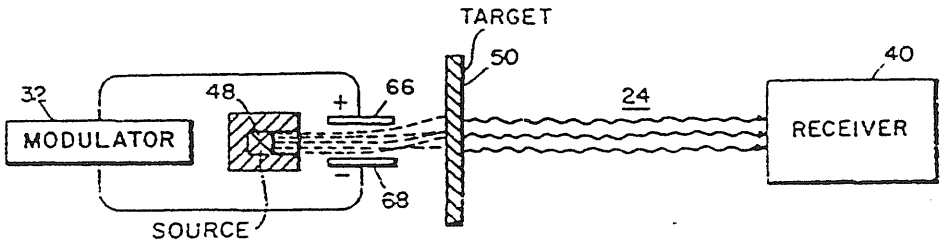

Fig. 4

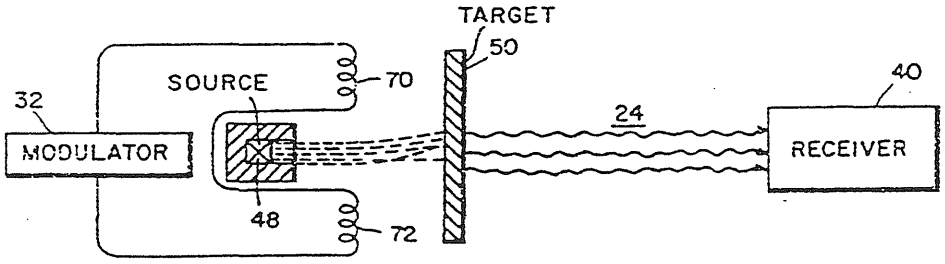

Fig. 5

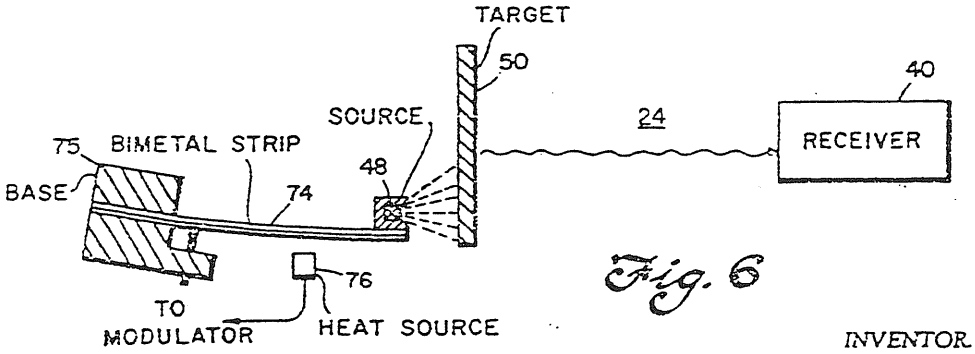

Fig. 6

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United States Patent Office 3,123,714 Patented Mar. 3, 1964

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SPACE COMMUNICATION SYSTEM

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Filed July 21, 1961, Ser. No. 125,797
6 Claims. (Cl. 250—199)

This invention relates in general to space communications systems and particularly to a communication system utilizing a modulated beam of bremsstrahlung radiation.

The success of the artificial satellites and the recent entry of man into space has made it evident that interplanetary travel with either manned or unmanned vehicles is not in the too far distant future. Communication between vehicles in space is essential, however. One of the primary difficulties confronting designers of all types of space apparatus is excess weight. For communication purposes, the conventional electronic transmitting and receiving systems, although acceptable for other uses, are too cumbersome for the futuristic designs of space vehicles. X-ray communication systems have been proposed—but again these systems are of the high energy and the high voltage type. The requirements for bulky electrical power generation devices automatically eliminate utilizing the conventional X-rays for space communications.

The present invention teaches a system that utilizes a radioisotope of the beta radiation emitting type and which radiation is utilized to excite a target to generate bremsstrahlung radiation. To convey intelligence the beta radiation beam is modulated or controlled before it strikes the target. The resultant bremsstrahlung is emitted from the target similarly modulated.

Accordingly, it is a general object of the present invention to provide a new and improved space communication system.

It is another object of the present invention to provide a space communication system utilizing bremsstrahlung energy.

A further object of the present invention is to provide a space communication system that is extremely compact and lightweight in comparison to other communication systems and does not require bulky electrical power generation devices.

Other objects and features of the present invention will become apparent from the following detailed specification taken in conjunction with the drawings in which:

FIG. 1 is a perspective view of a space communication system comprising a preferred embodiment of the present invention;

FIG. 2 is a diagrammatic illustration of the system shown in FIG. 1;

FIG. 3 is an illustration of a means for keying the radiation beam utilized in the preferred embodiment;

FIG. 4 is a diagrammatic view of a modulator for the system shown in FIG. 1;

FIG. 5 is an illustration of an alternative modulating system; and

FIG. 6 is an illustration of another modulating system useful in the preferred embodiment.

Referring to the drawings and specifically to FIG. 1, the transmission of information from one point to another is commonly accomplished by means of electromagnetic wave propagation techniques. The maximum distance of useful transmission is limited by the absorption characteristic of the medium traversed by the wave. Frequently surrounding a celestial body 10 such as the earth is a relatively dense atmospheric region R_1, wherein the energy of the transmitted wave may be absorbed. Outside these celestial bodies is a space region R_2 of negligible density having a correspondingly lesser attenuating effect on the transmitted wave.

Improved communication between space vehicles 12 and 14 or orbiting satellites 16 in extraterrestrial or extragalactic space is provided by the present invention. Accordingly, a transmitter of X radiation 18 receiving data 20 is coupled to a radiator 22 mounted on the vehicle 12. Data-encoded X radiation 24 is radiated toward the desired body.

The construction of the transmitter is shown in FIG. 2 wherein the transmitter comprises a beta-excited source 30 of X-rays or bremsstrahlung radiation, a modulator 32 and an intelligence signal generator 34. The radiant energy 24 from source 30 is modulated by modulator 32 in accordance with the output of the intelligence generator 34. The modulator 32 is more fully described hereinafter.

A receiver 40 is shown in dotted outline. The radiant energy 24 is detected by a demodulator 42. Demodulater 42 may be an ionization chamber or other suitable means known in the art to derive the intelligence signal from the radiant energy 24. The signal is amplified at 44 and utilized by means 46 in a known manner and for whatever purpose the original signal was conveyed.

Referring now to FIGS. 3–6 there are shown several alternative embodiments for modifying the bremsstrahlung radiation 24 for conveying intelligence information into the system. In FIG. 3 the source 48 may be a radioisotope, such as strontium 90 or krypton 85, that emits beta particles. There is disclosed in U.S. Patent No. 2,933,605 a measuring system utilizing bremsstrahlung. Also if it is convenient to use krypton 85 as a beta source there is disclosed in U.S. Serial No. 824,107, filed June 30, 1959, now Patent No. 3,094,622, a source-target arrangement that permits the filtering out of the unwanted gamma energy. A target 50 is mounted in the beam of beta particles 52 to generate the bremsstrahlung beam 24. Interposed between the source 48 and target is a radiation opaque shutter 54. This absorber, which could be a lightweight synthetic material, is arranged to move up and down within the primary stream of beta particles so as to key the stream of beta particles in accordance with the intelligence signal. In this way the incident beta particles are intercepted before striking the target 50. Accordingly, the energy emitted into space by the target would then contain the same information as was imparted to the primary beta ray beam.

Drive means for the shutter 54 is of conventional design and would principally be a rotary solenoid device 56 controlled by a keyer 58 and power supply 60. A spur and rack gear arrangement shown generally at 62 would then impart linear motion to the absorber 54. The electrical circuits for converting a message into currents suitable for activating the solenoid 56 are also of conventional design. Beam collimating and focusing expedients 64 for concentrating the bremsstrahlung radiation in the direction of receiver 40 also form a part of the system.

To avoid the use of mechanical linkages, an alternative embodiment such as that shown in FIG. 4 may be utilized. In this embodiment the electron beam 52 is modulated in accordance with an electric field across plates 66 and 68 in response to a signal from modulator 32. This field will cause the electrons to curve into or away from the bremsstrahlung target. The modulation of the electric field with its resulting modulation in the beta beam may alternatively be amplitude, pulse, or frequency modulated.

Another nonmechanical modulation embodiment is shown in FIG. 5 wherein the bremsstrahlung radiation field is magnetically modulated. The beta radiation passes through a magnetic field provided by a pair of coils 70 and 72 energized by modulator 32. The amount or degree of deflection can be regulated in accordance with the intelligence signal comprising the input to modulator 32. Changes in the magnetic field in turn modulate the resultant bremsstrahlung emitted by the target 50. It should

be noted the beta beam would be deflected in a plane perpendicular to the drawing; however, for purposes of facilitating the illustration, a deflection in the plane of the drawing is indicated.

Still another manner of modulating the radiation field in accordance with an intelligence signal is shown in FIG. 6. The modulating technique shown in FIG. 6 is fully disclosed in my copending application, Serial No. 56,849, filed September 19, 1960. In this embodiment the source of beta particles is mounted on a bimetallic temperature-sensitive strip 74 fixed to a base 75. A heat source 76 mounted adjacent to the strip 74 may be energized by the modulator 32 to change the angular position of the source 48 relative to the target 50. In this way more or less radiation is permitted to strike the target 50 and the amount of bremsstrahlung emitted is a function of the information contained in the intelligence signal. Alternatively, the source 48 may be fixed and the target 50 may be mounted on the bimetallic strip 74.

It should be noted that the energy spectrum of bremsstrahlung radiation 24 transmitted is determined primarily by the intensity of the originating electrons in the incident beta beam and the atomic number of the target 50. Provision may be made for changing from one target to another to concentrate most of the energy 24 in a predetermined wavelength band. The detector 42 may be rendered sensitive to this energy band by well-known techniques to improve the signal-to-noise response of the system. Likewise, targets of the same atomic number but of different thickness and shape may be utilized to control the amount of energy generated as well as the beam focusing characteristics thereof.

Although certain and specific embodiments have been shown, modifications may be made thereto without departing from the true spirit and scope of the invention.

I claim:

1. A system for conveying an intelligence signal from one point to another in a space region comprising a transmitter at one of said points including a nuclear source providing a beam of beta radiation, a target mounted in the path of said beam and adapted to generate bremsstrahlung upon bombardment of the atomic nuclei in said target by the beta particles in said beam, means for modulating the intensity of said beta radiation beam incident on said target in accordance with said intelligence signal whereby in turn the intensity of said bremsstrahlung is modulated in accordance with said signal, and a receiver at the other of said points including a detector for said bremsstrahlung radiation for demodulating the same to obtain said intelligence signal.

2. The communication system set forth in claim 1 in which said bremsstrahlung detector comprises an ionization chamber.

3. A system for conveying an intelligence signal from one point to another in a space region comprising a transmitter at one of said points including a nuclear source providing a beam of beta radiation, a target mounted in the path of said beam and adapted to generate bremsstrahlung upon bombardment of the atomic nuclei in said target by the beta particles in said beam; a shutter adapted to intercept a variable portion of said beta radiation beam between said beta radiation source and said target, means for moving said shutter relative to said beam to vary said portion, and means for driving said shutter moving means back and forth in accordance with said intelligence signal so as to modulate the intensity of said beta radiation beam incident on said target in accordance with said intelligence signal whereby in turn the intensity of said bremsstrahlung is modulated in accordance with said signal; and a receiver at the other of said points including a detector for said bremsstrahlung radiation for demodulating the same to obtain said intelligence signal.

4. A system for conveying an intelligence signal from one point to another in a space region comprising a transmitter at one of said points including a nuclear source providing a beam of beta radiation, a target mounted in the path of said beam and adapted to generate bremsstrahlung upon bombardment of the atomic nuclei in said target by the beta particles in said beam, means for producing a variable electric field for deflecting said beta particles in said beam between said source and said target, means for modulating said variable field producing means in accordance with said intelligence signal so as to vary said deflection, thereby modulating the portion of the energy of said beta radiation beam incident on said target in accordance with said intelligence signal whereby in turn the intensity of said bremsstrahlung is modulated in accordance with said signal, and a receiver at the other of said points including a detector for said bremsstrahlung radiation for demodulating the same to obtain said intelligence signal.

5. A system for conveying an intelligence signal from one point to another in a space region comprising a transmitter at one of said points including a nuclear source providing a beam of beta radiation, a target mounted in the path of said beam and adapted to generate bremsstrahlung upon bombardment of the atomic nuclei in said target by the beta particles in said beam, means for producing a variable magnetic field for deflecting said beta particles in said beam between said source and said target, means for modulating said variable field producing means in accordance with said intelligence signal so as to vary said deflection, thereby modulating the portion of the energy of said beta radiation beam incident on said target in accordance with said intelligence signal whereby in turn the intensity of said bremsstrahlung is modulated in accordance with said signal, and a receiver at the other of said points including a detector for said bremsstrahlung radiation for demodulating the same to obtain said intelligence signal.

6. A system for conveying an intelligence signal from one point to another in a space region comprising a transmitter at one of said points including a nuclear source providing a beam of beta radiation, a target mounted in the path of said beam and adapted to generate bremsstrahlung upon bombardment of the atomic nuclei in said target by the beta particles in said beam, means for mounting said source for movement relative to said target, means for varying the position of said source in accordance with variations in said intelligence signal so as to modulate the portion of said beta radiation beam incident on said target in accordance with said intelligence signal whereby in turn the intensity of said bremsstrahlung is modulated in accordance with said signal, and a receiver at the other of said points including a detector for said bremsstrahlung radiation for demodulating the same to obtain said intelligence signal, and means connected to said detector for indicating said intelligence signal.

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March 29, 1966 KIYO TOMIYASU ETAL 3,243,592

LASER PULSE COMMUNICATION SYSTEM

Filed April 16, 1963 2 Sheets-Sheet 1

Fig. 1.

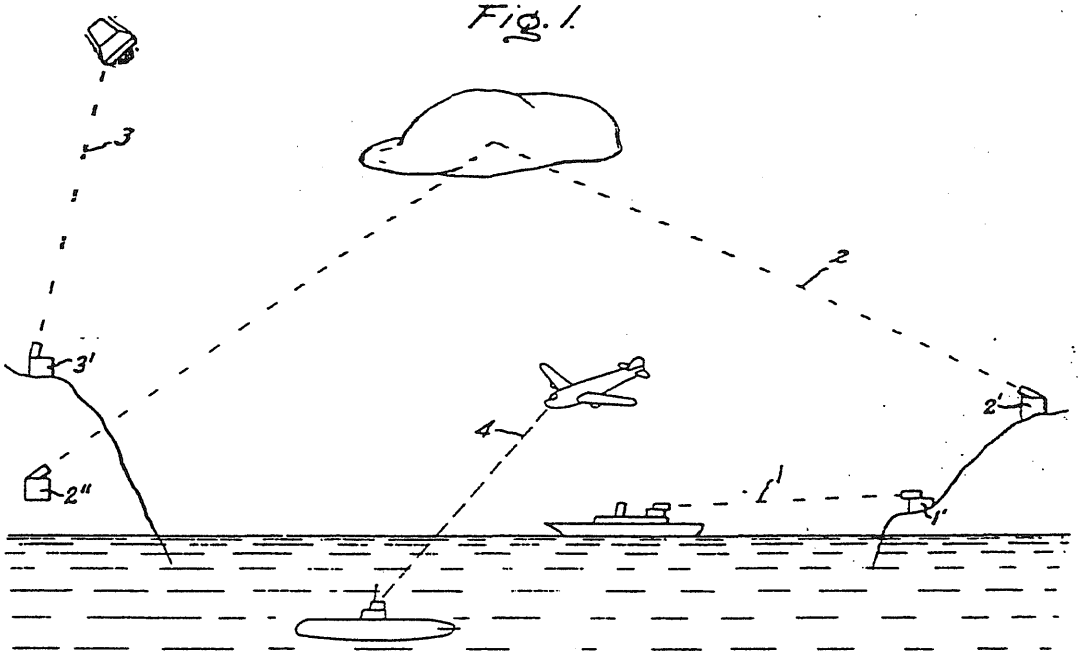
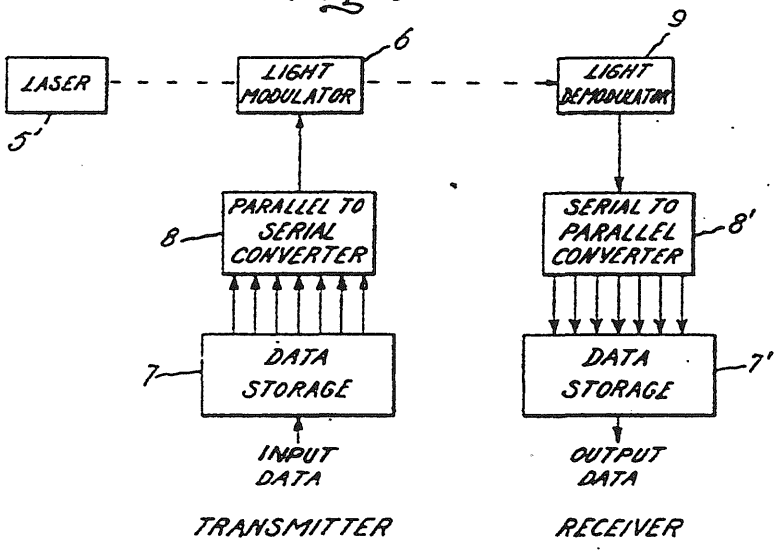


Fig. 2.



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LASER PULSE COMMUNICATION SYSTEM

Filed April 16, 1963 2 Sheets-Sheet 2

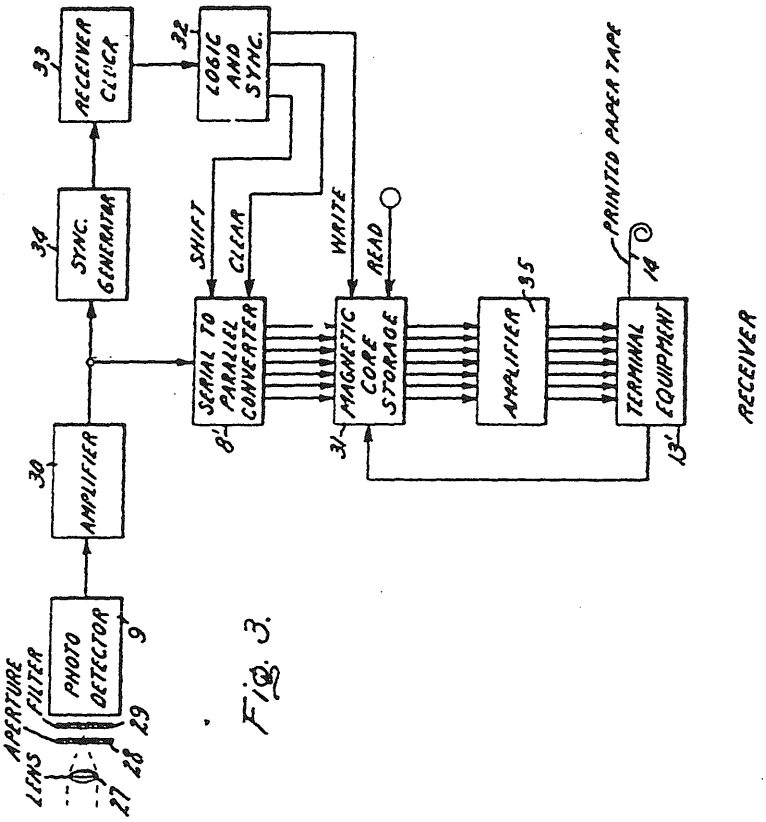
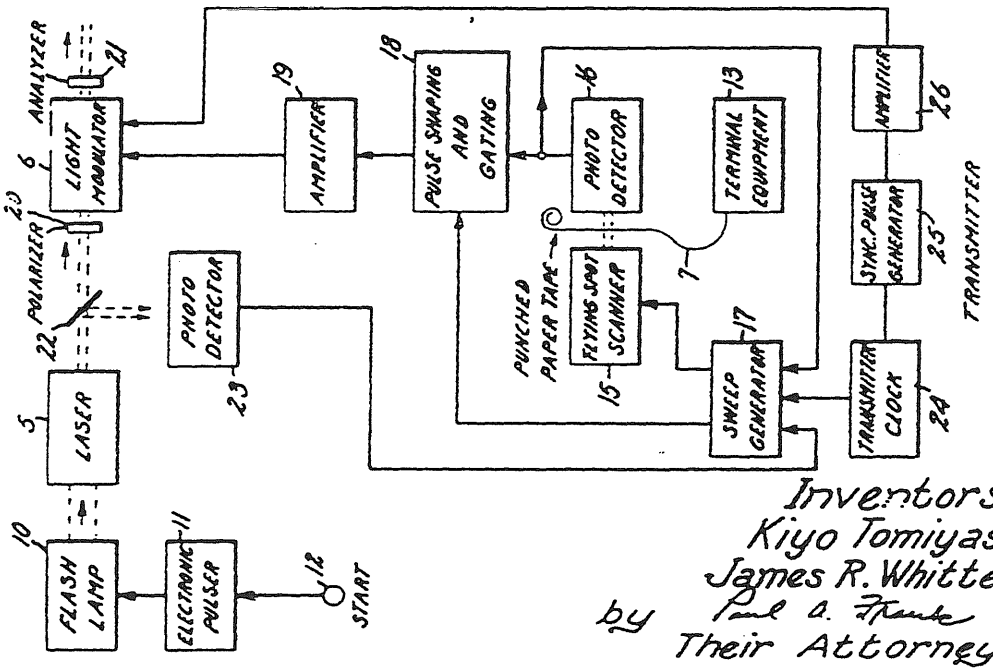


Fig. 3.



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LASER PULSE COMMUNICATION SYSTEM

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6 Claims. (Cl. 250—199)

Our invention relates to a communication system employing a pulsed laser device, and in particular, to a laser pulse communication system adapted to transmit and receive digital information at an extremely high rate of words per duration of laser pulse.

Communcation systems are conventionally defined by the frequency of electromagnetic energy or radiation upon which information is transmitted. This electromagnetic radiation is known as the carrier wave, and superimposed or modulated thereon is the information to be transmitted. The information modulation is generally described in absolute terms as an information bandwidth or modulation bandwith in units of frequency and as a percentage bandwidth or percentage modulation expressed as a percentage of the carrier frequency. The greater this information bandwidth or percentage bandwith, the greater the amount of information that is transmitted by the carrier wave. The percentage bandwith is generally limited to approximately 10 percent. As the carrier frequency is raised, a fixed percentage bandwidth becomes an increasingly larger information bandwidth which has the advantageous feature of increasing the available communication channels contained therein but also has the inherent disadvantage of occupying a greater portion of the spectrum of electromagnetic radiation. These two features are among the reasons why communication channels have been extended into the microwave spectrum of electromagnetic radiation. However, even this region of the spectrum is being rapidly occupied by the ever-increasing need for further communication channels. The need, therefore, exists to extend communication channels to an even higher frequency range in the spectrum of electromagnetic radiation and this next higher range includes the optical wavelengths.

One of the problems associated with optical communication systems is atmospheric scattering of visible light waves. A recently developed device, now conventionally described as a laser (light amplification by stimulated emission of radiation), offers a system capability which will not be as seriously degraded due to scattering as a system employing a more conventional light source. The output of a laser is a very narrow beam of light which is in the visible or near-visible frequency range of the electromagnetic energy spectrum. The energy within the light beam is exceptionally high since the light is concentrated within the narrow beam and also because the output of a laser may be a coherent light, that is, the particles of light emitted are in phase with each other. The high energy within the laser beam permits very long range communication, laser beams having been reflected from the surface of the moon, and the narrow beam feature renders the communication virtually free from detection and jamming.

Therefore, one of the principal objects of our invention is to develop a laser pulse communication system employing the pulsed output of a laser device to obtain a very narrow beam of pulses of light which may be adapted to carry a great amount of information.

Another important object of our invention is to develop a laser pulse communication system adapted to transmit and receive digital information at an extremely high rate of words per light pulse.

Briefly stated, and in accordance with our invention in meeting the objects enumerated above, we provide a laser device for generating a pulsed beam of light, the carrier wave, at the transmitter end of a communication system. A data storage circuit is employed to store input information in digital form and to provide this information in serial form suitable for transmission purposes during the interval of generation of laser or light pulses. The input information in serial form actuates an optical or light modulator which superimposes the digital information on the pulsed light beam. Pulse code modulation is the preferred method of modulating the light pulses. Suitable synchronizing circuits are provided to synchronize the output of the data storage circuit with the light pulses emitting from the laser.

The receiver end of the communication system includes a suitable optical arrangement for collecting the light pulses, a demodulator to convert the light pulses to electrical signals, a data storage circuit, suitable synchronizing circuits, and a device for reading the output of the data storage.

The features of our invention which we desire to protect herein are pointed out with particularity in the appended claims. The invention itself, however, both to its organization and method of operation, together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with the accompanying drawings, wherein:

FIGURE 1 illustrates several communication paths for the pulsed laser beam which may be employed with our invention;

FIGURE 2 represents a basic block diagram of a laser pulse or burst communication system in accord with our invention; and

FIGURE 3 is a detailed block diagram indicating the various components of a laser pulse communication system in accordance with our invention.

A laser pulse communication system may be described as a communication system having a transmitter end that emits energy in the visible and near visible wavelength spectrum of electromagnetic radiation and consists of discrete pulses of this energy. This spectrum includes the infrared, optical, and ultraviolet frequencies and is contained within a range of 10^7 to 10^9 megacycles per second. A given percentage of information bandwidth at such frequencies is a larger absolute bandwidth in cycles per second than occurs with the same percentage bandwidth at the lower radio and microwave frequencies and thereby provides a greater amount of available communication channels. For comparison, at microwave frequencies, the available information or modulation bandwidth is limited to a small percentage of the carrier frequency, usually about 10 percent, which thus provides a modulation bandwidth of about 1000 megacycles at X-band. At a laser output frequency of 3×10^8 megacycles per second, a very modest bandwith of about 1 percent represents a modulation bandwidth of 3,000,000 megacycles which is sufficient to transmit approximately one million television channels.

Laser pulse communication is effected by generating short duration pulses of high intensity and preferably coherent light at the transmitter end of the system. These pulses of light, which may conveniently be generated by a laser device, are modulated with the information desired to be transmitted. The laser light pulses are of short duration and merely by way of example may be in the order of 0.001 second duration. The modulation impressed on the laser pulses is preferably a pulse code modulation described in greater detail hereinafter.

A laser releases electromagnetic energy stored in discrete metastable states as a result of being excited by an electromagnetic signal of the correct frequency. Thus, a flash lamp may excite or optically pump the laser into a metastable higher energy state whereby a stimu-

lated emission of monochromatic and directional (coherent) electromagnetic radiation is emitted from one end of the laser. This electromagnetic radiation or light is emitted in a plane wave having a very small divergence, in the order of 0.05 degree or less. This small divergence concentrates the energy of the laser into a beam of very intense light, thereby achieving a very high energy density and permitting long distance line-of-sight communication.

The laser pulse communication system of our invention is not limited to line-of-sight applications. Thus, the high energy concentration within the narrow light beam may be reflected from sharply defined clouds, buildings, and orbiting satellites for nonline-of-sight communication applications. Another distinct application of our pulse communication system is communication through a plasma of ionizable gas. Radio frequencies cannot propagte through a plasma formed about a space vehicle during the time the vehicle is re-entering the atmosphere since the radio frequency is too low compared to the plasma frequency and the radio signal is reflected thereby. The plasma frequency is $9000\sqrt{n}$ cycles per second, where n is the number of electrons per cubic centimeter. During re-entry, n may be typically 10^{16} and no higher than 10^{17}. Thus to penetrate the plasma, the frequency of the signal must be higher than 3×10^{12} cycles per second. A ruby laser frequency is 4.3×10^{14} cycles per second and, hence, this laser beam readily passes through the densest re-entry plasma. A second requirement for laser communication through a plasma is that the spectral temperature of the laser output be appreciably higher than that of the plasma at the laser frequency. This requirement is necessary to attain a discernible signal-to-noise ratio. The spectral temperature of a pulsed ruby laser is in the order of 10^9 to 10^{12}° K. and the plasma temperature is about 10^4° K. An optical filter at the receiver is preferably employed to perform an analogous function of the tuning circuit in a radio frequency receiver. If this optical filter cannot be made as narrow as the laser output bandwidth, there will be a degradation in the signal-to-noise ratio. This degradation will be in a range from 10^{-2} to 10^{3-}. A discernible signal-to-noise ratio is produced even with this degradation.

A laser pulse or burst communication system may also be employed for transmission through an air-water interface. The state of the sea surface, that is, the change in the surface due to the moving position of the waves of water, has frequency components in the audio range and it is, therefore, difficult to transmit audio signals using an electromagnetic wave carrier since the sea state seriously degrades the signal-to-noise ratio. A burst communication system transmits rapidly, the bursts or pulses having a time interval of the range of one millisecond. The necessarily high modulation frequencies superimposed on this pulsed carrier insures transmission through the air-to-water interface before the sea state has changed significantly.

The several methods of laser pulse communication hereinabove described are pictorially represented in FIGURE 1 wherein line-of-sight communication is represented as a whole by numeral 1, nonline-of-sight or reflected communication by numeral 2, communication through a plasma 3, and communication through an air-to-water interface 4. Land-mounted transmitters and receivers constructed in accordance with our invention are designated as 1', 2', 2'' and 3' corresponding to the line-of-sight communication 1, reflected communication 2, and communication through plasma 3.

A basic functional block diagram of a laser pulse communication system is illustrated in FIGURE 2. At the transmitter end of the system, input data, which comprises the information to be transmitted, is supplied from terminal equipment and converted from oral or recorded form to electrical quantities which are employed to modulate pulses of high intensity and preferably coherent light emitted by a pulsed laser device 5. A light modulator 6 may be of the transmission type wherein the modulation is impressed externally on the laser output or possibly the source type wherein the modulation is developed within the laser material. At the receiver end of the system, output data which comprises the received information is supplied to terminal equipment to provide a recorded output of this received information. The terminal equipment at both the transmitter and receiver ends comprises conventional message encoders, preferably of the high speed type. These message encoders have a data handling rate much slower than the rate at which the input data is transmitted in accordance with our invention. For this reason, intermediate data storages 7 and 7' and data converters 8 and 8' may be utilized at the transmitter and receiver ends, respectively. For maximum utilization of data storage capacity, especially at the transmitter end, the storage is emptied in the duration of the laser pulse.

Transmitter noise, especially in a system employing a ruby laser and inherent receiver noise provide a serious degrading effect in the performance of conventional analog modulation techniques. However, digital modulation tolerates a considerable amount of receiver and transmitter noise and is preferably employed in our invention. This noise level is decreased by maintaining the laser in a cooled atmosphere.

As one example of digital modulation, eight digits are used for each element of information or character. The digitized information is in the form of six digits per character, a seventh digit is employed as an error detection bit known as a parity check bit, and an eighth digit for character synchronizing purposes. A minimum transmission rate of 400 words per one 0.001 second duration light pulse per second is achieved in accordance with our invention, assuming 40 digits or bits constitute the average length word. For this particular minimum rate of transmission, the intermediate data storage 7, 7' capacity is 16×10^3 bits per pulse and the data rate converter 8, 8' has a data handling rate of 16×10^6 bits per second. Data rate converter 8 may be a parallel-to-serial converter at the transmitter end and converter 8' a serial-to-parallel converter at the receiver end. These types of converters are employed since digital information is most conveniently stored in parallel form but is transmitted in serial form. It should be understood, however, that these converters and data storage devices are unnecessary in the event a message encoder is operable at a data handling rate of 16×10^6 bits per second. In like manner, the converters are unnecessary when employing a data storage device which stores digital information in serial rather than parallel form. A light demodulator 9 is employed in the receiver end for detecting the transmitted light pulses and converting the digital information contained therein into electrical signals.

The detailed block diagram illustrated in FIGURE 3 indicates a preferred embodiment of our invention. Laser 5 is 2 x 0.25 inch ruby rod contained within an inner housing which comprises liquid-nitrogen cooled double-walled Pyrex tube, it being understood that other laser materials and suitable containers may also be employed. An outer housing having an ellipsoidal reflecting surface is employed to support the ruby rod and inner housing at one focus of the ellipsoid and a straight xenon flash lamp 10 at the other focus. The flash lamp is disposed parallel to the ruby rod and is employed as the optical pump and is rated at 1000 joules. An electronic pulser 11 of conventional circuitry actuates the flash lamp at the appropriate times; in this particular embodiment the actuation being at the rate of once a second. The operation of electronic pulser 11 may be programmed and each sequence begun by pressing start button 12. Electrical

connections are designated by solid lines in FIGURE 3, conventional light outputs by widely spaced-apart dashed lines, and coherent light beam by closely spaced-apart dashed lines.

Terminal equipment 13 and 13' at the transmitter and receiver ends, respectively, includes the message encoders and may, by way of example, comprise a high speed teletypewriter which punches or prints a paper tape at a speed of 60 words per minute. Punched paper tape 7 at the transmitter end is used as a data storage mechanism and printed paper tape 14 at the receiver end is employed as the received information display element. A flying spot scanner circuit 15 reads the punched paper tape 7 at a prescribed bit rate of 16×10^3 bits per 0.001 second by passing a sequential binary coded light signal, corresponding to the holes in punched paper tape 7, through a suitable converging lens (not shown) to photodetector 16. The contents of a prescribed length of the paper tape is thus converted to a plurality of serial electrical pulses at the output of photodetector 16. Flying spot scanner circuit 15 comprises an electron gun supplied with a sweep voltage of step wave form applied to one set of deflection plates and a sweep voltage of a sawtooth wave form applied to a second set of deflection plates wherein the two sets of plates are disposed in perpendicular relationship. The two sweep voltages are supplied from sweep generator 17 and they deflect the flying spot scanner beam over the perforated paper tape. A suitable pulse shaping and gating circuit 18 assures the synchronization of the serial binary electrical pulses with the laser pulse. The output of circuit 18 consists of square wave pulses wherein each pulse represents one bit of the input information. The square pulses are amplified to a peak of 5 kilovolts by a conventional wide frequency band power amplifier 19 in order to be of proper magnitude of power and voltage to provide approximately 50 percentage modulation of the light beam passing through light modulator 6.

The pulsed coherent light output from laser 5 may be modulated either within the laser material itself by techniques known as Zeeman or Kerr cell modulation or external to the laser by using a transmission type modulator such as a Pockels, Kerr, or Faraday cell or traveling wave structure. The specific light modulator employed in our optical pulse communication system is a transmission type Model JW-1 electro-optical light modulator. This modulator is a variable phase-retardation device which linearly controls the relative phase difference of orthogonal components of the polarized light passing through it in proportion to the magnitude of an impressed electric field. Since this device requires polarized incident light, an input polarizer 20 is placed between the laser output and the input to the light modulator to reject unpolarized light. Alternatively, ruby rod 5 may be cut such that the crystal axis is at 90° to the rod axis and polarizer 20 is thereby not required. The output of amplifier 19 supplies the electric field to light modulator 6. The characteristics of the Model JW-1 modulator are such that 100 percent modulation (half-wave retardation) of the laser output is obtained with a modulation voltage of 9000 volts at 0.5 micron wavelength. The maximum frequency of operation of this modulator is 1.6×10^6 cycles per second at maximum voltage and a continuous duty cycle. The frequency limitation is determined by the power losses in the metallic electrodes required to produce the electric field in the modulator crystal. However, at reduced operating voltage or reduced duty cycle, this maximum modulation bandwidth is increased since the power loss varies directly with these factors. Thus, a modulation bandwidth of 25 megacycles, which represents a bit rate of 50 megabits per second (three times that required to transmit 400 words during the interval of a 0.001 second pulse per second), may be obtained with 100 percent modulation and a 0.001 duty cycle. The power loss within the JW-1 crystal at this modulation bandwidth is approximately 1.25 milliwatts. The average power required to achieve this bandwidth is approximately 3 watts per megacycle bandwidth or 75 watts at a 0.001 duty cycle. Thus, amplifier 19 need have an average power output rating of approximately 25 watts for the required bandwidth representing 16 megabits per second. An output polarizer or analyzer 21 is positioned at the output of light modulator 6 and converts the modulated wave to intensity or amplitude modulation by passing only the properly polarized light.

Sweep generator 17 is operable at a frequency of 16×10^6 cycles per second and synchronized to provide the properly timed vertical and horizontal sweeps to flying spot scanner 15 at the beginning of each light pulse generated by laser 5. The signal for the synchronization is attained by means of a beam splitter 22 which is positioned intermediate the laser output and polarizer 20 and a photodetector 23 which detects the beginning of this light pulse and supplies a signal to initiate the operation of sweep generator 17. Sweep generator 17 is further synchronized by the system or transmitter clock 24 to insure that the horizontal and vertical sweeps occur exactly in phase with the information holes punched on paper tape 7 and thereby generate the information bits at a constant rate at the output of amplifier 19. The output of sweep generator 17 provides a second input to the pulse shape and gating circuit 18 to provide a coincidence signal whereby the output of photodetector 16 may be varied to coincide with the transmitter clock synchronizing signals. Nonlinear hole spacings which may occur in the punched tape 7 are compensated for by providing an output from photodetector 16 as a third input to sweep generator 17. As hereinbefore described, the digitized information is in the form of an eight digit binary code wherein six digits or bits form one character. The eighth digit is used for character synchronizing purposes and is supplied by means of a serially connected transmitter clock 24, synchronous pulse generator 25 and amplifier 26. This eighth digit is transmitted on the laser beam in the form of a signal cross-polarized relative to the polarization of the other seven digits on the beam. The fly-back time of the flying spot scanner occurs during the interval of the eighth digit.

The light demodulator portion of the receiver in our laser pulse communiaction system detects the modulation on the light beam by means of an optical system consisting of collecting lens 27, aperture 28 to reduce background light, an optical interference filter 29 which provides an optical bandwidth preferably as narrow as the light modulator 6 output bandwidth to further reduce background light, and polarization-sensitive photodetector 9 which is a photoemitter device such as a photomultiplier appropriate to the 4.3×10^{14} cycles per second radiation being detected. This optical system is conveniently contained within a suitable telescope body. The output signal of photodetector 9 consists of binary pulses or bits occurring at a 16×10^6 bits per second rate. This output is amplified by a conventional wide frequency band voltage amplifier 30. The information as described by the binary bits is displayed by means of a relatively slow operating terminal equipment 13', such as a teletypewriter, thus an intermediate data storage device such as a magnetic core storage unit 31 is required. A serial-to-parallel converter 8' is utilized to convert the serial form of digital information available at the output of amplifier 30 to a parallel form suitable for storage purposes in magnetic core storage unit 31. The data rate of converter 8' is a minimum of 16×10^6 bits per second and the storage rate of magnetic core storage unit 31 has a minimum capacity of 16×10^3 bits per 0.001 second which is the duration of the light pulse transmitted by the laser. Converter 8' which is a shift register and unit 31 are of the type employed in electronic digital computers. Synchronization of the serial-to-parallel converter 8' and

magnetic core storage unit 31 with the transmitted data during the data storage cycle is achieved by means of a logic and synchronization circuit 32 which detects the signal representing each eighth digit, the character synchronizing or cross-polarized bit of information. Alternatively, a seven digit binary code may be employed, the synchronizing being accomplished by means of a receiver clock 33 and a logic and synchronization circuit 32. In this alternative case, instead of an eighth or cross-polarized bit, a series of synchronizing pulses are transmitted by transmitter clock 24 immediately preceding each transmitted message. These synchronizing pulses provide a positive synchronization between transmitter clock 24 and receiver clock 33 by actuating synchronous pulse generator 34 which in turn initiates receiver clock 33. After the received message has been stored in the core storage unit 31, the core storage address register is reset, the core is addressed at a rate determined by the speed of the terminal equipment 13', and the message is read into the terminal equipment upon voltage amplification of the core signals by a conventional electronic amplifier 35 and printed on paper tape 14.

From the foregoing description, it can be appreciated that our invention makes available a new system of pulse or burst communication employing the visible and near-visible range of the electromagnetic radiation spectrum as the carrier for the information to be transmitted. The pulses of high intensity light are modulated by the information to be transmitted. This information is converted to digital form to provide improved performance in the presence of receiver and transmitter noise. As lasers are further developed, information in analog form may be employed to modulate the laser output. Further, the information transmission rate may be increased as improved lasers permit pulse repetition rates greater than one pulse per second and the generation of longer duration laser pulses. The information transmission rate is presently limited by the peak bit rate of present day commercial serial-to-parallel converters. As this converter peak bit rate is increased to the modulation bandwidth limitation of present day light modulators (25 megacycles per second), and assuming a 0.001 pulse duty cycle, an information transmission of 50 megabits per second is provided thereby transmitting approximately 1250 words per 0.001 second burst.

Having described a new laser pulse communication system, is believed obvious that modifications and variations of our invention are possible in the light of the above teachings. Thus, the transmitter end of the system illustrated in FIGURE 3 may be similar to the receiver end, that is, employ a magnetic core storage unit and parallel-to-serial converter in place of the serial-to-parallel converter circuit which includes the punched paper tape 7, flying spot scanner, and photodetector 16. Further, thermoplastic tape, a shift register, electronic devices employing flip-flop circuits, electrostatic charge storage tubes and image orthicons may be utilized as data storage means. Also the pulse code modulation employed is not limited to a binary code of a particular number of bits per address and may include other suitable codes. Finally, the modulation at the transmitter end may be developed within the laser rather than externally thereof. It is, therefore, to be understood that changes may be made in the particular embodiment as described which are within the full intended scope of our invention as defined by the following claims.

What we claim as new and desire to secure by Letters Patent of the United States is:

1. A communication system adapted to transmit and receive digital information comprising in combination

means for storing digital input information at the transmitter end of the system,

means for generating a high intensity beam of light consisting of relatively short duration pulses at the transmitter end,

means for modulating the light pulses with a wide information bandwidth comprising the input information,

means for receiving and demodulating the transmitted light pulses and thereby providing the information at a receiver end of the system remote from the transmitter end,

means for synchronizing the sequence of information contained on the transmitted and received light pulses,

a serial-to-parallel converter connected to an output of said demodulating means, and

means connected to the output of said serial-to-parallel converter for storing the digital information at the receiver end whereby the received information may be read out at a desired time.

2. A pulsed laser beam communication system adapted to transmit and receive digital information through a plasma of ionizable gas comprising in combination

means for generating a highly directional and collimated beam of coherent light at the transmitter end of the system, said light beam consisting of relatively short duration pulses of intense light characterized by a narrow spectral width,

means for storing digital input information in parallel form at said transmitter end,

a parallel-to-serial converter connected to the output of said input information storage means whereby said digital input information may be read out in serial form,

means for pulse modulating the light pulses with a wide frequency bandwidth comprising the digital input information in serial form whereby the pulse modulated light beam is transmitted at a frequency substantially higher than the frequency of the plasma through which said light beam passes and the spectral temperature of the output of the coherent light generating means is substantially higher than the spectral temperature of the plasma at the frequency of the coherent light generating means,

means for receiving and demodulating the transmitted light pulses at the receiver end of the system remote from the transmitter end,

means for synchronizing the sequence of digital information contained on the transmitted and received light pulses,

a serial-to-parallel converter connected to the output of said demodulating means, and

means connected to the output of said serial-to-parallel converter for storing the digital information at the receiver end whereby the received information may be read out at a desired time.

3. A pulsed laser beam communication system adapted to transmit and receive digital information through an air-water interface comprising in combination

means for generating a highly directional and collimated beam of coherent light at the transmitter end of the system, said light beam consisting of relatively short duration pulses of intense light characterized by a narrow spectral width,

means for storing digital input information in parallel form at the transmitter end,

means for reading out the digital input information in serial form,

means for modulating the light pulses with a wide frequency bandwidth comprising the digital input information in serial form whereby the modulation frequencies are transmitted through an air-water interface in a relatively short time during which the surface of the water has not changed significantly,

means for receiving and demodulating the transmitted light pulses at the receiver end of the system remote from the transmitter end whereby the digital information is provided at said receiver end,

means for synchronizing the sequence of the digital information contained on the transmitted and re-

ceived light pulses, means for converting the serial form digital information at the output of said modulating means to parallel form, and

means connected to the output of said serial-to-parallel converting means for storing the digital information at said receiver end whereby the received information may be read out at a desired time and at a relatively slow rate.

4. A pulse communication system adapted to transmit and receive digital information comprising in combination

means for generating a high intensity beam of light characterized by a narrow spectral width and consisting of relatively short duration pulses at the transmitter end of the system,

means for storing digital input information on tape at the transmitter end,

means for reading the tape at a selected rate of words per duration of light pulse,

means connected to the output of the tape reading means for generating a sequential binary code corresponding to the digital information stored on the tape,

means for modulating the light pulses with a wide information bandwidth comprising the sequential binary code,

means for receiving and demodulating the transmitted light pulses and thereby providing the information in serial form at the receiver end of the system remote from the transmitter end,

means for synchronizing the sequence of the digital information contained on the transmitted and received light pulses, and

means for storing the digital information at the receiver end whereby the received information may be read out at a desired time.

5. A laser pulse communication system adapted to transmit and receive digital information during the interval of laser pulses comprising in combination

means for generating a high intensity beam of coherent light consisting of relatively short duration laser pulses at the transmitter end of the system,

means for storing digital input information on tape at the transmitter end,

means for reading the tape at a predetermined time and at a selected rate of words per duration of laser pulse,

means for synchronizing the initiation of the tape reading means with the beginning of each laser pulse,

means connected to the output of the tape reading means for generating a sequential binary code corresponding to the digital information read from the tape,

means for modulating the laser pulses with a wide frequency bandwidth comprising the sequential binary code whereby said binary code is transmitted at said transmitter end,

means for receiving and demodulating the transmitted laser pulses whereby said binary code is received at a receiver end of the system remote from the transmitter end,

means for synchronizing the received binary code with the transmitted binary code,

a serial-to-parallel converter connected to an amplified output of said demodulating means, and

means connected to the output of said serial-to-parallel converter for storing the digital information in parallel form at the receiver end whereby the received information may be read out at a desired time.

6. A laser pulse communication system adapted to transmit and receive digital information at a minimum rate of 400 words per laser pulse of approximately 0.001 second duration comprising in combination

means for generating a high intensity beam of coherent light consisting of at least one laser pulse of approximately 0.001 second duration per second at the transmitter end of the system,

means for storing digital input information at a minimum rate of 2×10^6 addresses per second having eight bits per address,

a parallel-to-serial converter connected to the output of the digital storage means, said converter having a minimum operating rate of 16×10^6 bits per second,

means including a beam splitter disposed in the path of the laser beam for synchronizing the initiation of the parallel-to-serial converter and digital storage means with the beginning of each laser pulse,

means for pulse code modulating the laser pulses with a wide frequency bandwidth containing the digital input information whereby the transmission of a laser pulse empties the input information storage means at a minimum rate of 400 words per duration of laser pulse,

means including a lens, aperture, optical filter, and a photoelectric device for receiving and demodulating the transmitted laser pulses at a receiver end of the system remote from the transmitter end,

a serial-to-parallel converter connected to the output of the demodulating means, said serial-to-parallel converter having a minimum operating rate of 16×10^6 bits per second,

means for storing the received digital information at a minimum rate of 16×10^6 bits per duration of laser pulse whereby the received information may be read out at a desired time and at a relatively slower rate, and

synchronized transmitter and receiver circuits for transmitting and receiving the digital information in correct sequence.

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May 2, 1967 P. R. CALAWAY 3,317,729

SYSTEM FOR DETERMINING MISS-DISTANCE USING A GAMMA RAY SOURCE AND DETECTOR

Filed May 14, 1963 8 Sheets-Sheet 1

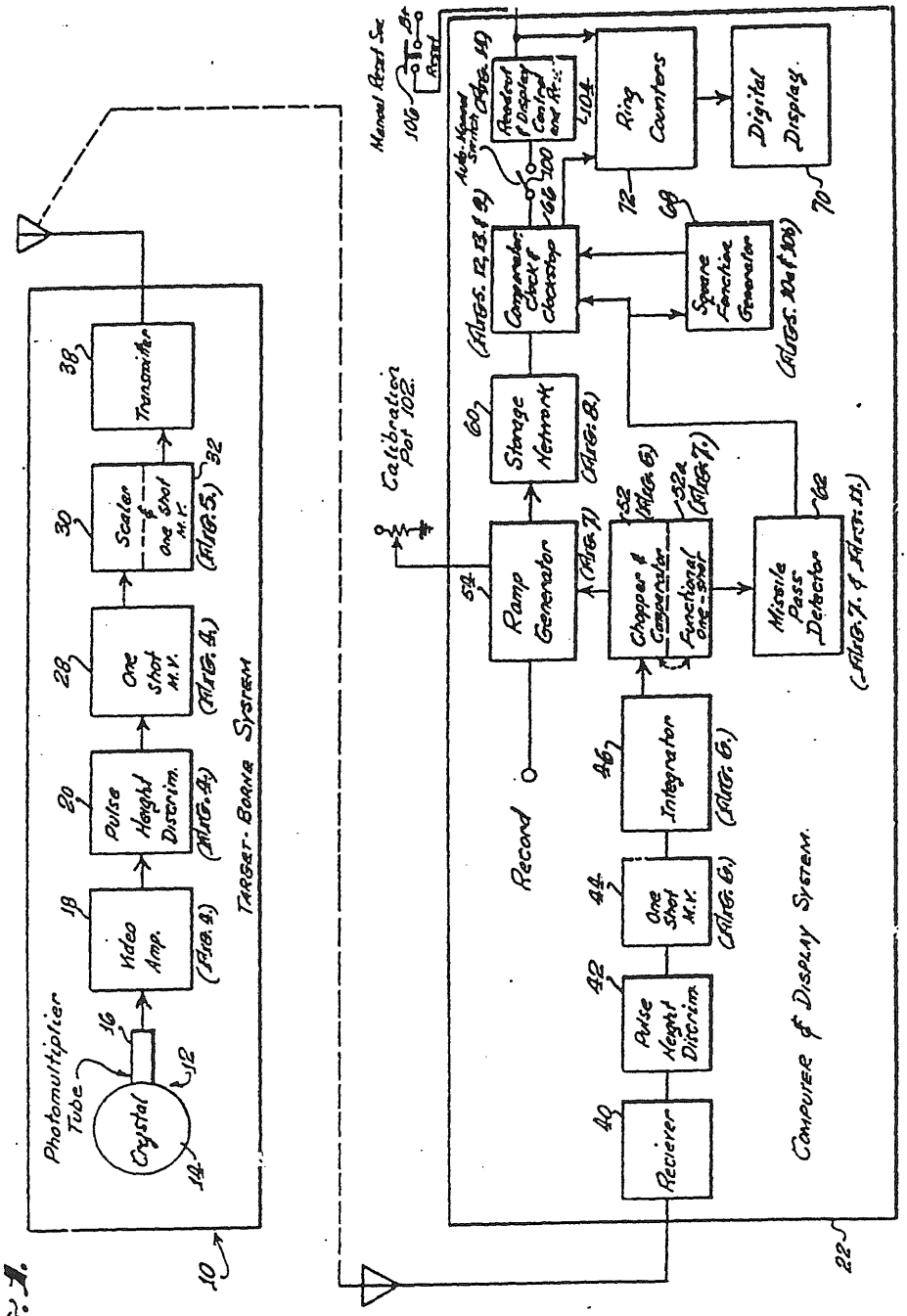

FIG. 1.

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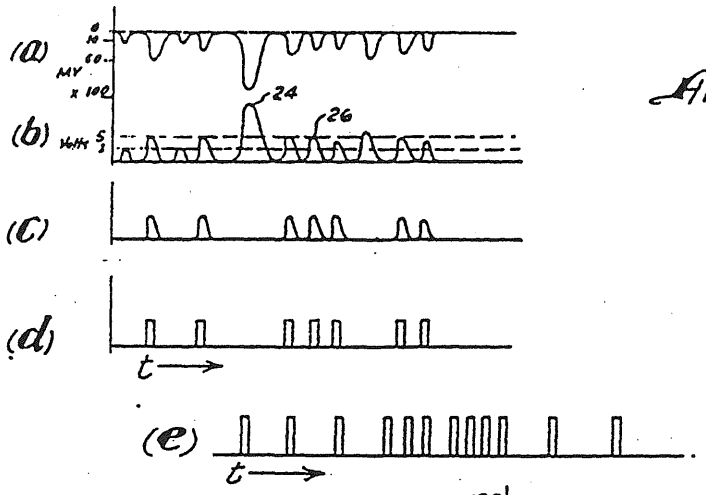
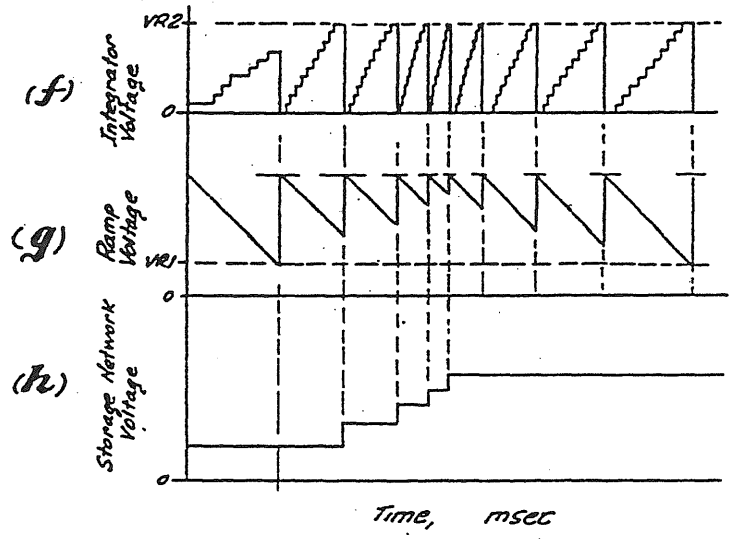


FIG. 2.



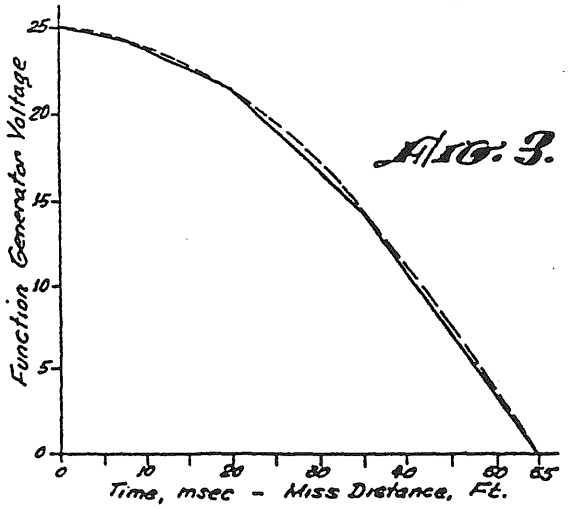


FIG. 3.

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SYSTEM FOR DETERMINING MISS-DISTANCE USING A GAMMA RAY SOURCE AND DETECTOR

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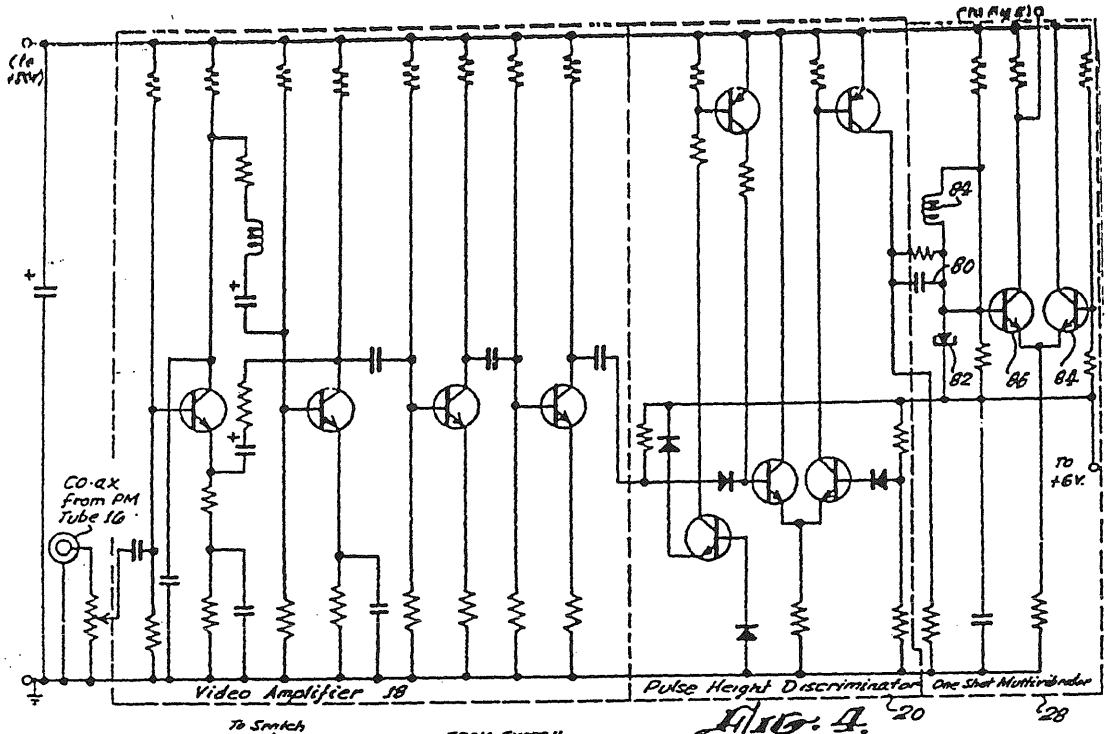

FIG. 4.

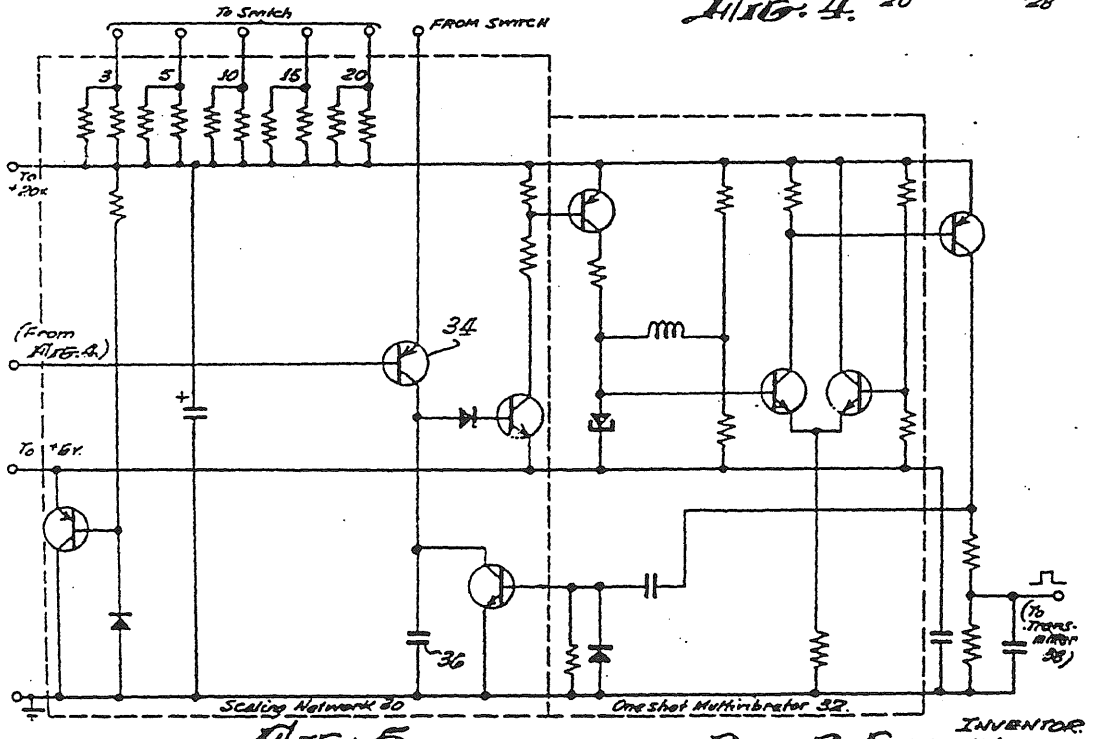

FIG. 5.

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SYSTEM FOR DETERMINING MISS-DISTANCE USING A GAMMA RAY SOURCE AND DETECTOR

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Fig. 6.

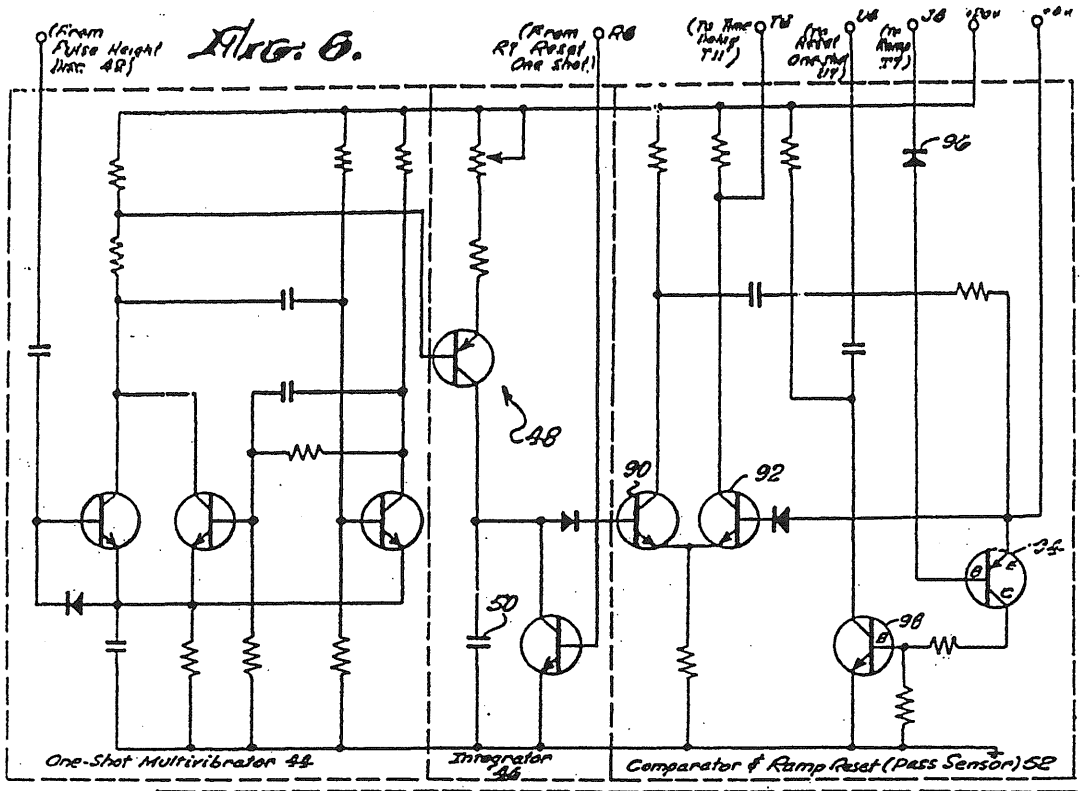
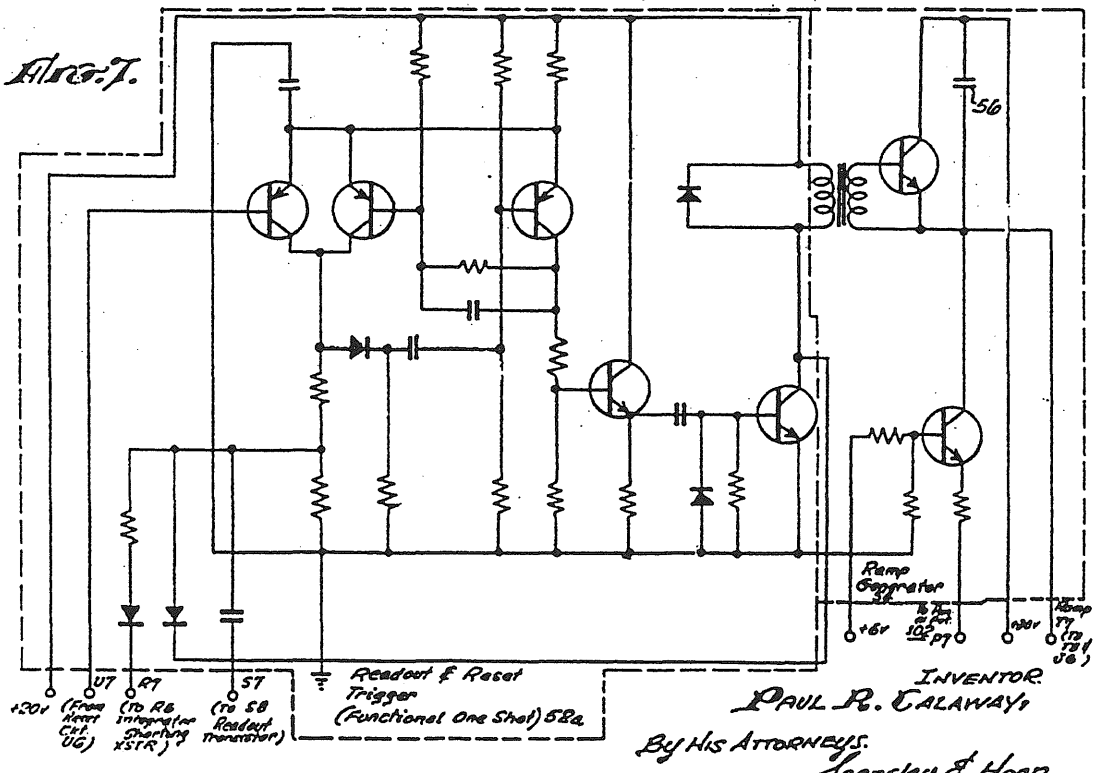


Fig. 7.



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SYSTEM FOR DETERMINING MISS-DISTANCE USING A GAMMA RAY SOURCE AND DETECTOR

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Fig. 8.

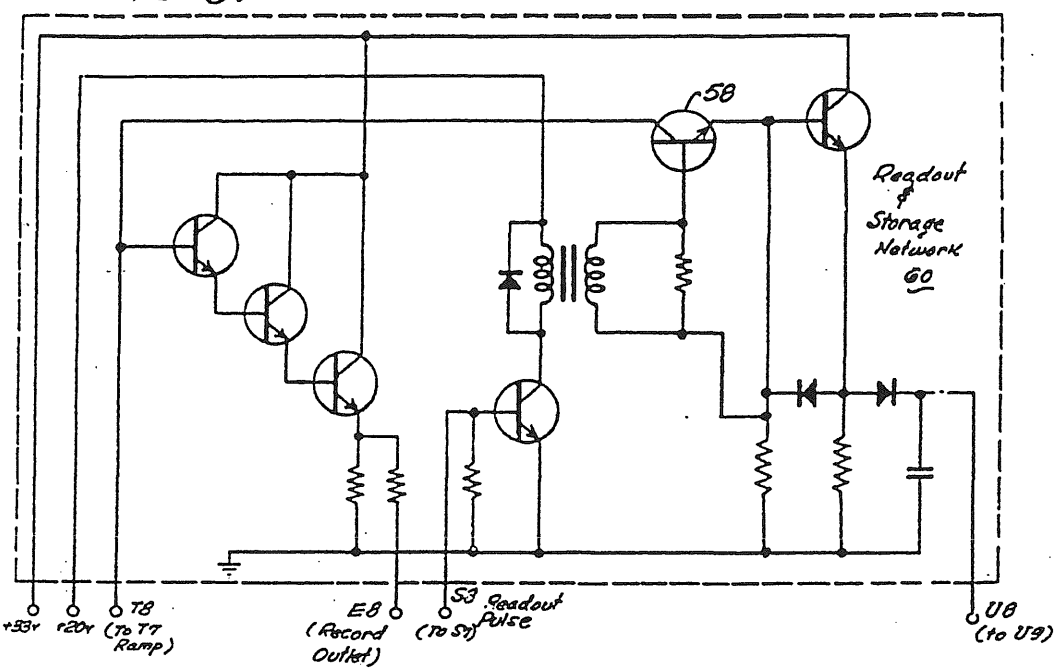
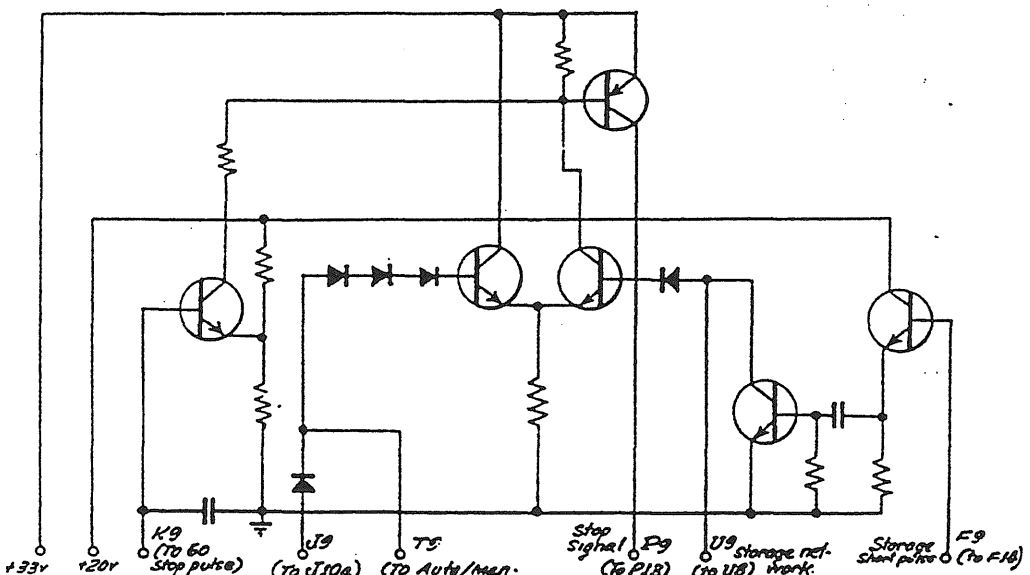


Fig. 9.



Clock Stop Trigger & Comparator 66

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SYSTEM FOR DETERMINING MISS-DISTANCE USING A GAMMA RAY SOURCE AND DETECTOR

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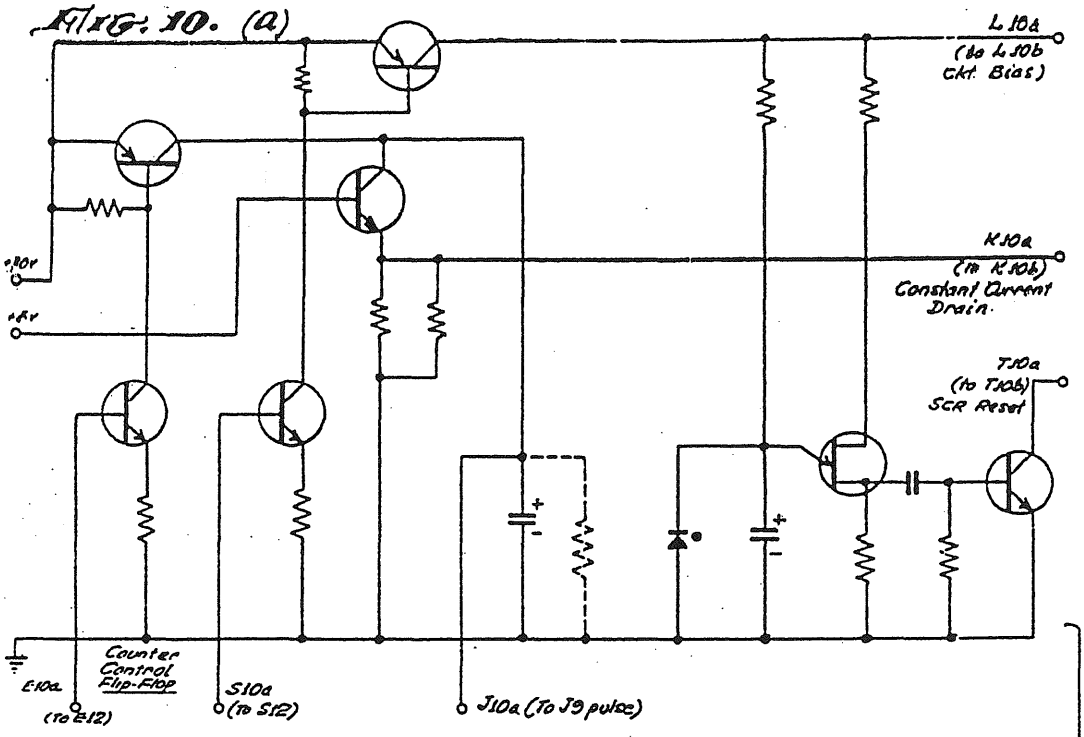
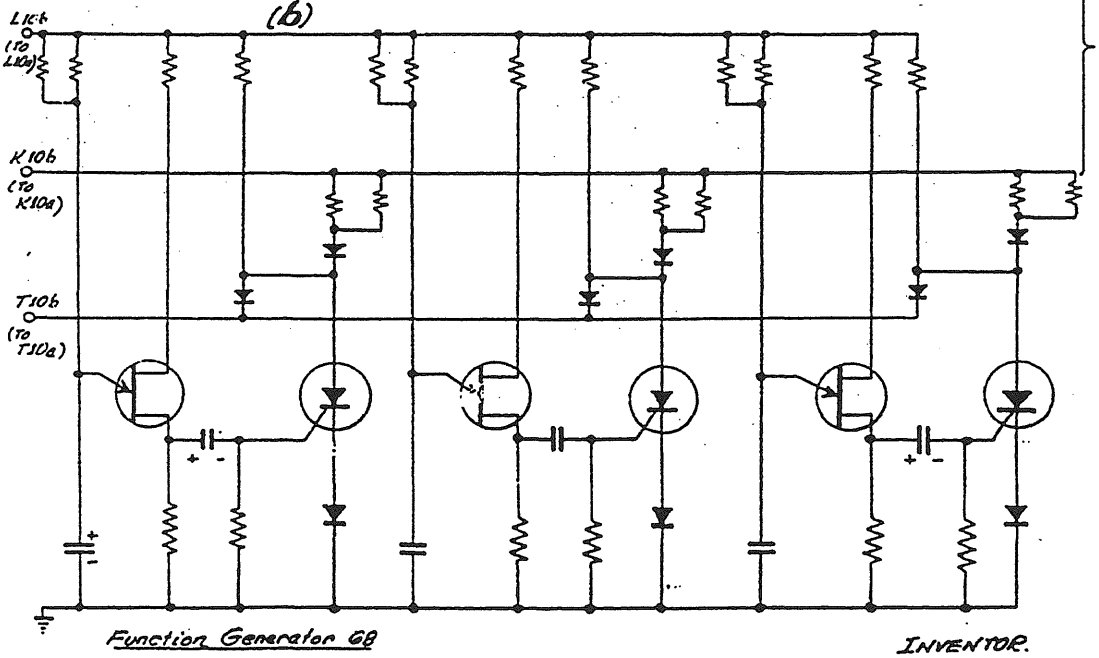
FIG. 10. (a)



(b)



Function Generator 68
(Figs. 10a & 10b)

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SYSTEM FOR DETERMINING MISS-DISTANCE USING A GAMMA RAY SOURCE AND DETECTOR

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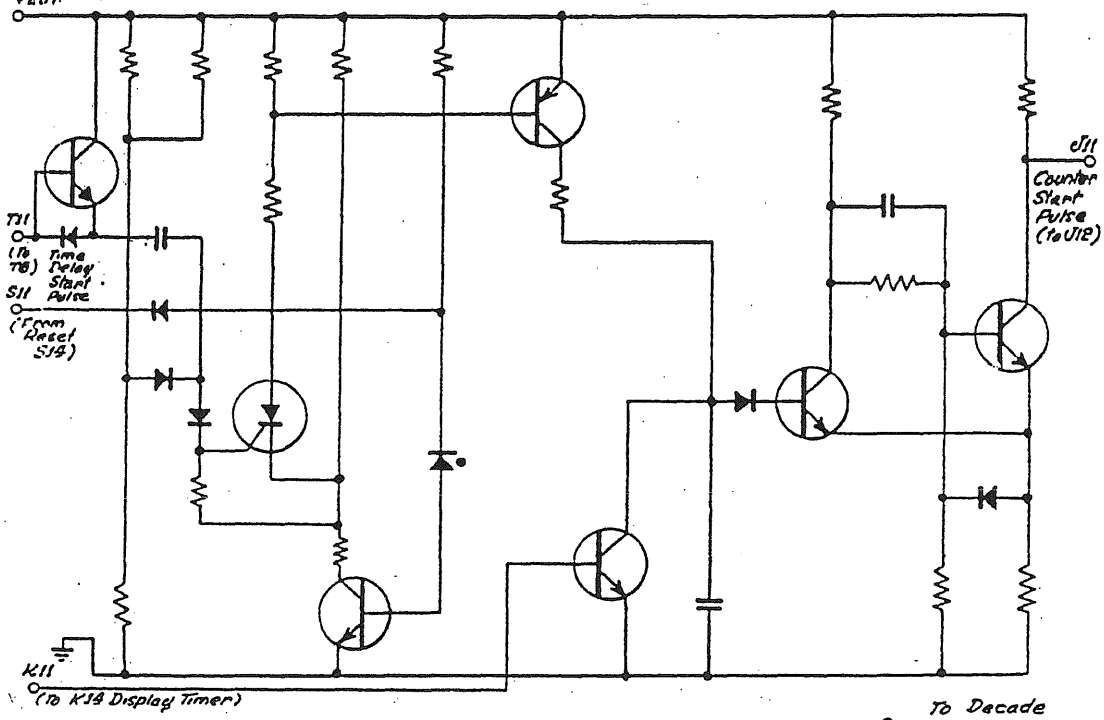
FIG. 11. Clock-Delay & Clock-Start Ckts.



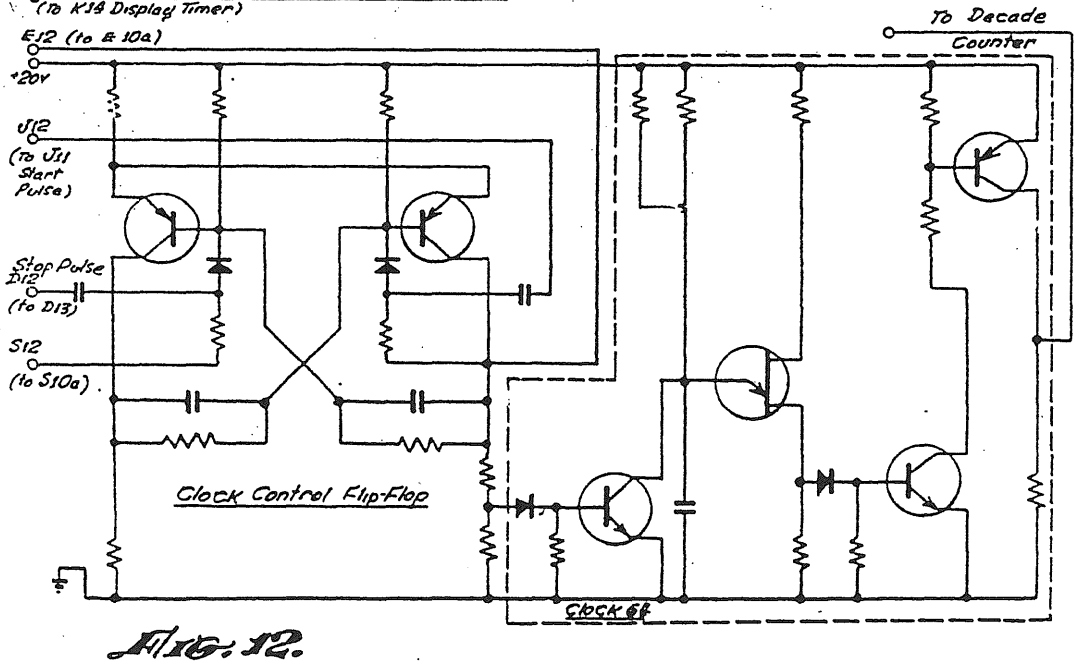


FIG. 12.

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SYSTEM FOR DETERMINING MISS-DISTANCE USING A GAMMA RAY SOURCE AND DETECTOR

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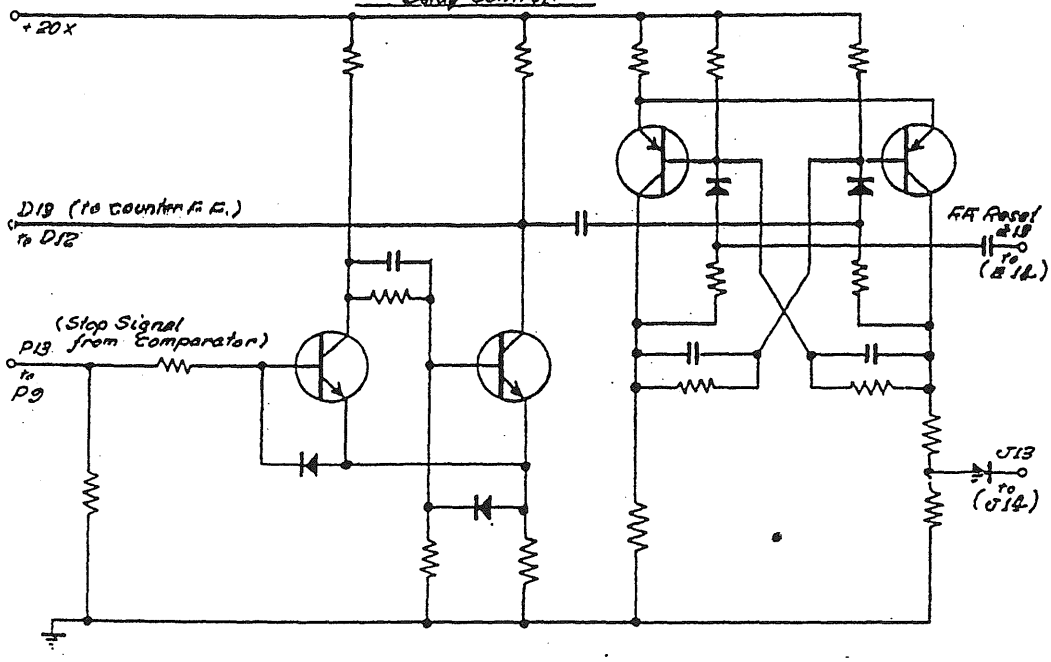
FIG. 13. Clock Stop and Readout Delay Control.



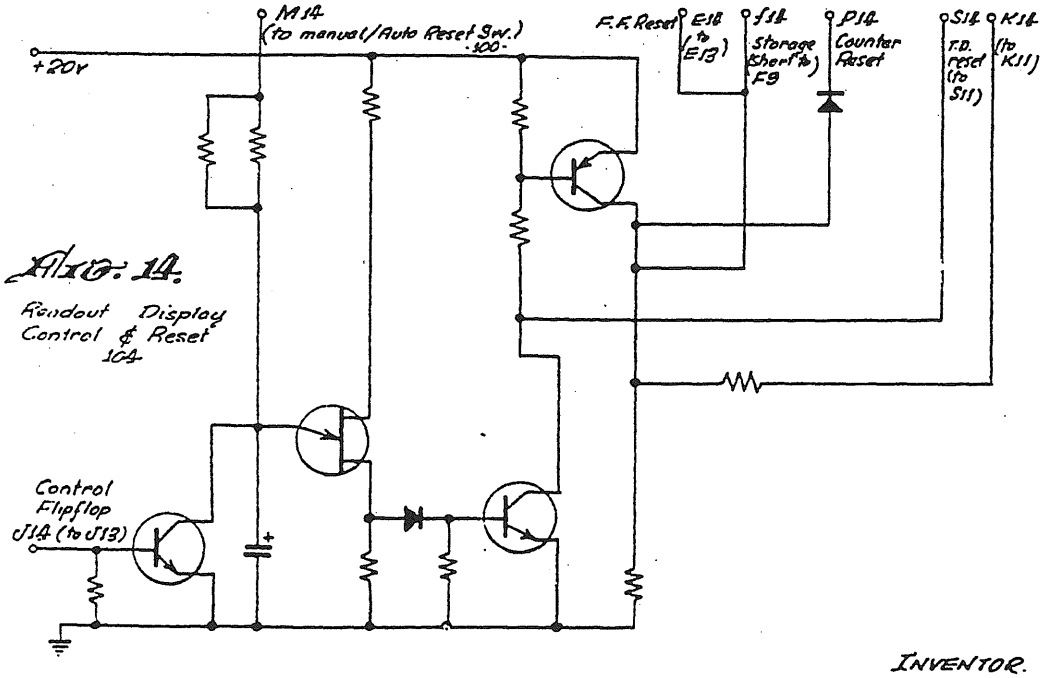


FIG. 14. Readout Display Control & Reset 104

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United States Patent Office

3,317,729

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SYSTEM FOR DETERMINING MISS-DISTANCE USING A GAMMA RAY SOURCE AND DETECTOR

Paul R. Calaway, Glendale, Calif., assignor to Electronic Specialty Co., Los Angeles, Calif., a corporation of California

Filed May 14, 1963, Ser. No. 280,205
6 Claims. (Cl. 250—71.5)

This invention relates to a distance indicator, and more particularly to such a system employing a gamma-radiation source in one object which may be detected in another to determine their closest separation distance during relative movement.

Accurate separation or miss-distance information is required for analysis of the reliability and accuracy of relatively moving objects, such as practice targets and missiles, and particularly those missiles which utilize a proximity fuse, thus eliminating the necessity for direct hits to destroy or disable the target. For firing practice, when using a drone-type target, a built-in miss-distance factor is sometimes added to the missile's steering mechanisms to prevent a direct hit and the destruction of the target. When the missile comes within this predetermined miss-distance, it is considered to have made a direct hit and the drone is kept intact for the next missile firing.

While expensive and complex targets are thus not destroyed and may be used for repeated missile firing during a firing practice, it is extremely important to know how close the missile approached the target, preferably before the next missile firing mission so that suitable corrective measures may be taken.

Because of the high altitudes and relative speeds between the target and missile, direct visual systems are not practical. Photographic triangulation, acoustical and Doppler-radar systems have been tried, but for the most part have been quite complex, too expensive, require a large power source, are heavy and ineffective for practical miss-distance measurement applications. Moreover, they do not provide for immediate miss-distance information.

More recently, gamma-radiation detection systems have been used for accurately detecting, measuring and indicating rapidly changing radiation intensity levels. The radiation intensity received by a scintillation detector varies with its dstance from the radiation source and this principle forms the basis for scintillation-type detectors.

Unlike most other miss-distance systems, the missile-borne equipment of a radiation miss-distance detection system is simple and inexpensive; consisting of merely a small, activated gamma-ray source. As the missile is generally non-recoverable, a great saving in cost is realized. The activated tag, mounted on the missile, is so small that the missile dynamics are not affected at all by its presence. This means that test missiles can be identical to combat missiles with no expensive modifications necessary. No interference with radar systems or other communication links is experienced when using such a miss-distance indicator. Because of their high energy, the gamma-rays are not affected in any manner by the ionized boundary layer encountered with extremely high-speed vehicles. Also, attenuation from the air between the missile and the target is small. The decay rate of the activated gamma-ray source is completely independent of the missile environment and can be chosen to be very long compared to the duration of a firing mission. Thus, after a static calibration on the ground, the source strength can be considered to be a system constant. The equipment installed in the target can be minimized with the readout equipment mounted in the monitor plane, on the ground, or both. This will also result in a cost reduction in case of a malfunction resulting in the loss of a target. System

reliability is also enhanced. Since gamma-ray detection methods are inherently digital (each gamma ray detected results in a single count), the readout problems are reduced. This also increases the system reliability.

One such system employs a source of gamma rays placed in a missile, a detector in the target, and a data reduction system on the ground or in a piloted aircraft for an observer. Output signals are produced by the detector in response to each incident radiation photon and the data reduction system receives the information in the form of pulses. The number of pulses received during a predetermined interval of time are proportional to the radiation intensity which varies according to the distance separating the radioactive source from the detection equipment. This information is then translated into an indication of whether the missile carrying a radioactive source was within the critical destruction distance of the target carrying the detection equipment.

This scintillation-type of scoring system is less costly and less difficult to install and use than other types of scoring systems. For example, most scoring systems using radar techniques incorporate a transponder mounted inside the attacking missile, thereby changing the actual combat characteristics. Complex target-borne equipment is necessary. The ground stations receiving transmission from the transponder equipment in the target involve rather complex and expensive computers.

In scintillation-type scoring systems, a small radioactive tag is installed within the missile; on a ring fitted around the missile, or in a bolthead which is screwed in either a tail fin or some other convenient location. The gamma-radiation emitted from the tag on the missle is then received at the target by a scintillation-type radiation sensor, and no communication link between the missile and the target is necessary in order to recover miss-distance information. The circuitry required in the target-borne detection system typically includes a video amplifier to amplify the pulse information which results from the impingement of the gamma-radiation on a radiation sensor. A pulse-shaping circuit typically is involved and a modulating network for the transmitter for transmission of the pulse data to the ground station. Thus, the cost of installation and maintenance of a radiation-type scoring system, both for missile and target, is substantially less than any of the other types of scoring systems.

Most scintillation-type scoring systems to date receive at the readout station essentially the same type of data input, the data input being in the form of pulse information with the pulse repetition rate being a function of the instantaneous missile tag range from the target-borne sensor. The frequency of the pulses over a predetermined length of time is then transformed into distance information. Thus, these radiation detection systems operate by setting a discrete time interval and measuring or counting the pulses received during that time.

In such a system which samples pulses for a discrete time interval, error due to missile velocity during that time interval is a continually changing factor. During this sample time, the range from the sensor to the missile changes linearly. At the end of the fixed sample time, the range as determined by the number of counts collected is always greater than the actual missile range on an approach. The difference between the actual range and the range as determined from the count rate, assuming negligible statistical error, is the so-called velocity error.

Assuming the missile velocity to be constant, the missile moves the same distance during each sample period. Error due to missile velocity in a constant-sample time system is small at large ranges, but it becomes significantly larger as the missile approaches the target. Therefore,

percent error at long range is less than percent error at close range because distance travelled is essentially the same during the sample time.

Another disadvantage in previous scintillation scoring systems lies in the nature of the statistical errors incurred. The accuracy of scintillation scoring systems depend primarily on the statistical nature of the activated gamma source. Since the actual decay rate of a radioisotope is of a random nature, the radiation of gamma rays is not really a constant with time, and with this radiation as a range measuring source, there is a statistical variation in the accuracy of the system. In these previous systems, during a missile pass, the total counts in a constant time interval which indicates minimum range, can vary by a factor of one hundred or more. A radiation count over a period of time converted into distance, then, will not measure distance with a constant statistical accuracy. If the radiation count is extended over a relatively long period of time, the effect of these statistical fluctuations can be reduced to a negligible value. However, over a longer period of time, the velocity error increases. A compromise usually is made between gathering a large sample of gammas and establishing a short enough time base so that the missile range does not change significantly.

The distance indicator comprising the present invention overcomes these defects of earlier systems by operating in a novel manner which permits compensation for the range errors due to missile velocity through instrument adjustment prior to the missile firing. Also, the statistical error is fixed at some known value, thus enabling the operator to be able to establish the same confidence level for all missile firings and miss-distances. This system is based upon a technique of counting a preselected number of pulses and determining the time it takes to receive this number of pulses, the time being a function of distance. The further away the missile is from the target, the longer it takes to count the selected number of pulses. The time to count the same number of pulses is much less than when the missile is closer, so that the percent of error will nearly always be the same. This velocity error, being a constant percentage of the distance, can then be compensated for in the equipment and in this manner greater accuracy can be achieved. The measurement of the time required to count a preselected number of pulses due to the random radiation of gammas, especially after calibration of the system during a sample test before firing practice, makes the system much more predictable than systems which relate the gamma count rate to a fixed time. This is because the gamma count rate is an inverse square function of source range and thus the confidence level and statistical accuracy are extremely difficult to establish with a constant sample time.

The distance indicator system of the present invention, in one embodiment, consists of a radioactive tag placed in the missile, a radiation detector and telemetry device placed in the target and a ground station or station in a monitoring aircraft for converting detection information into distance information. As the missile containing the radioactive tag approaches the target, the rate of impingement of gamma rays on the scintillator crystal in the target increases. The intensity of the impingement of gamma rays is inversely proportional to the square of the range:

$$N=\frac{K}{R^2}$$

where N equals the number of gamma rays/unit time arriving at the detector, R equals the range or separation distance, and K equals a constant. The gamma-ray impingement information is converted to electrical pulses which are telemetered to the ground station where this information is then converted into a readout of the minimum separation distance of the missile from the target.

The system operates on the principle that a preset

number of constant-height and constant-width (thus constant-energy) pulses, when integrated, will attain a certain voltage level, and the time required to integrate to this level varies linearly with the count rate. Since the count rate is inversely proportional to the square of the separation distance between the missile and the target, the time duration in charging the integrating capacitor is also proportional to the square of the range.

This time duration is related to a function which produces a second time base which is linear with distance. This is done by first controlling the output from a ramp generator with the aforementioned integrator level by resetting the ramp at the same time the integrating capacitor is reset. The integrator appears as a series of voltage staircase functions of constant peak amplitudes, but with the time bases of the staircase functions of magnitudes which are proportional to the square of the missile-to-target range. The modified ramp wave shape then contains a voltage analog of the missile's approach path to the target. This voltage is stored in a storage network until a readout circuit is activated by a missile path detector. The maximum storage voltage amplitude represents the closest approach of the missile to the target. Making the voltage proportional to the measurable time duration linear with distance requires further transformation.

The missile pass detector, sensing an increase in pulses above a given level generates, after a time delay, a pulse that triggers the readout system and activates a square function generator. The voltage on a capacitor in the function generator is discharged at a rate proportional to the square of time until it is equal to the voltage in the storage network; thus converting the voltage amplitude into miss-distance. In this manner, the time interval until the two voltages are equal is a direct function of the range, rather than a square function as was the integrating time interval. A clock operating during this time interval, is then used to drive a decade display that sums the number of clock pulses and displays it in terms of separation or miss-distance.

It is therefore an object of the present invention to provide a novel distance indicating system based on gamma-radiation detection.

Another object is to provide for a miss-distance indicating system of great reliability and accuracy, yet which is simple and inexpensive to make, install and operate and which is relatively lightweight and compact.

Another object is the provision of a miss-distance indicating system wherein the time required to count a selected number of gamma radiations from an object is proportional to the square of the separation distance of a detector from that object.

Another object of the present invention is the provision of a radiation-type distance detection system for converting the time required to sample a selected number of radiations into an indication of distance.

Another object is the provision of a miss-distance indicating system wherein the magnitude of velocity error is reduced in accordance with separation distance to provide for a constant percent velocity error for which a compensation may be made.

Another object is the provision of a radiation-type distance indicator wherein statistical error due to randomness of radiations is fixed by relating the time to count a selected number of radiations to distance instead of relating the radiation rate to distance.

Yet another object is the provision of a radiation-type distance detection system wherein velocity errors may be calibrated out by adjustment of a voltage ramp slope in sampling radiations before use.

Still another object is to provide a distance indicating system wherein radioactive radiation from a missile is converted into pulses by apparatus on a target and wherein these pulses are collected and used to control a sawtooth waveform to obtain a voltage analog of separation distance.

A further object is the provision of a miss-distance indicating system wherein the shortest separation distance between two relatively moving objects is extracted from a voltage analog of the square of the separation distances which has been stored as a maximum voltage level, and wherein this voltage level may be compared with a square function wave voltage level over a linear time interval; the time interval until equation of said voltage levels being directly proportional to the shortest separation distance.

These and other objects will become apparent as a description of the invention proceeds, having reference to the drawings, wherein:

FIGURE 1 is a block diagram of the system;

FIGURE 2 shows the principle wave forms utilized in the system;

FIGURE 3 shows a waveform of the function generator;

FIGURES 4 and 5 are circuit diagrams of the target-borne system; and,

FIGURES 6 through 14 are circuit diagrams of various portions of the data processing and readout system.

Referring now to the block diagram in FIGURE 1 with reference to the wave forms in FIGURES 2 and 3, there is shown the target-borne system 10 which operates from a target drone, not shown. Within this system, a radiation detector 12 in one form may consist of a spherical crystal 14 and photomultiplier tube 16. The crystal is preferably of polyvinyl toluene and in one embodiment is on the order of about seven inches in diameter. Each gamma which passes through the crystal excites some number of electrons determined by the statistical considerations. When these electrons return from their excited state to their ground state, they emit photons of light in approximately the 4000 A. region. The outside of the crystal has been coated with a black epoxy paint to prevent the outside ambient light from affecting the photomultiplier tube. The scintillation crystal 14 has been covered on the inside with a light-reflecting substance which allows these light photons to reflect about the crystal until they are received at the photocathode of the photomultiplier tube 16. When these photons impinge upon the photocathode of the phototube, photoelectrons are generated. These electrons are then accelerated through the tube and operate in standard fashion as in all photomultiplier tubes. Both the scintillation crystal 14 and the photomultiplier tube 16 are conventional devices readily available on the market today. Crystals can be typically purchased from Nuclear Enterprises, Ltd. in Winnipeg, Canada, and photomultiplier tubes are available from organizations such as RCA and Dumont. The output from the photomultiplier tube is a negative going pulse of varying amplitude shown as waveform (*a*) in FIGURE 2. These pulses are the result of three functions:

(1) the signal input caused by the gamma-radiation impinging on the crystal;
(2) inherent tube noise usually of lower level within the photomultiplier tube itself; and,
(3) cosmic radiation, cosmic background which usually results in much greater magnitude pulse heights than the pulses resulting from the gamma radiation. Pulse height from the phototube due to the gamma radiation varies typically from 10 to 50 millivolts.

The video amplifier 18 employed is of a standard wide-band transistorized type with three stages of gain, effect establishes a voltage window which eliminates the pulses above a preset height and also below another preset level, as shown by waveform (*c*). This is done for the following reasons: The low-level tube noise described earlier can cause degradation of the system accuracy by appearing to the computer and display system 22 as a gamma count. In addition, the cosmic radiation level which varies by a factor 10 from sea level to 50,000 feet altitude will also degrade the accuracy of the system for the same reason. These pulses, due to cosmic radiation, as mentioned earlier, are typically much greater than the pulse due to a gamma photon impinging on a scintillation crystal. Pulse 24 may be compared with pulse 26 as an example. Therefore, a window was selected which will accept all pulses between approximately 1 volt and 5 volts, this level being established in this embodiment as those pulses caused by the reaction between a gamma photon and the scintillation crystal 14. By operating this window, some of the signal will be lost since there is a finite, although small, probability that one of the low-level or one of the extremely high-level pulses is a result of a gamma reaction. However, the advantages to be gained by eliminating the noise more than offsets the disadvantage of losing some of the signal with this type of network. The circuit diagram of the pulse height discriminator is shown in FIGURE 4.

The output from the pulse height discriminator 20 is then fed into a one-shot multivibrator 28. This one-shot multivibrator is of the tunnel diode variety and is quite unique in that it can provide an extremely high pulse repetition rate and maintain a stable pulse height and pulse width. Pulse repetition frequencies of 3 megacycles are typical in this circuit, the diagram of which is shown in FIGURE 4. The reason for driving the one-shot multivibrator 28 is to provide a pulse of constant-height and constant-width for each pulse which passes through the pulse height discriminator 20. Thus, one constant-energy pulse is recovered for each gamma which reacts with the scintillation crystal 14 in the beginning of the system. These pulses, shown as (*d*) in FIGURE 2, are then much easier dealt with in the following circuitry.

These pulses from the one-shot multivibrator 28 are then fed into a scaling network 30. The reason for this scaler is strictly to divide down the pulse rate for telemetering of the data by the target-borne transmitter. This technique enables the system to handle higher gamma photon count rates from larger radioactive tags and still remain within standard IRIG telemetering band width. The IRIG standards define telemetering characteristics for all U.S. military installations, including telemetering band width, pulse repetition rate, frequency stability, spurious responses, etc. IRIG is the abbreviation for the Interrange Instrumentation Group which group is located in White Sands, New Mexico, and sets standards for Data Transmission and Reception in Missile Ranges.

A second one-shot multivibrator 32 is provided at the output of the scaler 30 to provide a constant-height, constant-width pulse for a preset number of pulses into the scaler network due to the gamma reaction. The scaler network can be described as follows: The output from the first one-shot multivibrator 28 drives a constant-current generator 34 during the pulse duration.

different division factors are obtainable. This sensor system provides five preset division factors which can be obtained by merely plug-in means or by rotation of a switch, not shown. These factors have been set to be 3, 5, 10, 15 and 20, enabling the system to operate at minimum ranges for tag strength ranging from less than 5 millicuries to more than 100 millicuries of Antimony 124, or its equivalent. These numbers identify switch positions in FIGURE 5.

The output from the second one-shot multivibrator 32 modulates a telemetering transmitter 38. This transmitter is a standard airborne solid state transmitter which is readily available and performs the conventional function of transmitting pulses. One such typical transmitter is marketed by Electronic Specialty Co., Los Angeles, Calif. The scaling network 30 is permanently adjusted so that for a given tag strength at minimum missile range, the pulse repetition rate to the transmitter 38 is never more than approximately 30 kc. with pulse width of approximately 10 microseconds.

The pulse formation from transmitter 38, such as pulses shown as waveform (*e*) in FIGURE 2, is recovered from a standard telemetering receiver 40, such as Nems-Clark Model No. 1455A, and is thus fed into the computer and display system 22. This system can be packaged in three possible configurations in order to provide optimum usage:

(1) a 19" rack configuration for a permanent installation;
(2) a portable transit case which is provided with a water-tight cover for work in remote locations;
(3) a combination of a computer module and a readout module which is mounted in an airplane cockpit so that the scoring information is available during flight.

The pulse data from the receiver 40 is fed into a pulse height discriminator 42 in order to eliminate any noise which may be generated within the receiver 40 or in the data link between the receiver and the computer. This is especially useful when operated with the cockpit readout unit because of the amount of radio noise generated by the rotating machinery, generators, etc., within the aircraft. Suitable scopes and recorders (not shown) may be connected at this point for display or retention of the received signal. These pulses then drive a one-shot multivibrator 44, also of conventional design, as shown in FIGURE 6, in order to provide pulse reshaping in the event that there is some degradation of the pulse shape by a transmitter or the receiving equipment. The output from the one-shot multivibrator is a constant-height, constant-width pulse, similar to the transmitted pulses in waveform (*e*) to provide a convenient operation in the later circuitry.

The output of the one-shot multivibrator 44 is fed into an integrating network 46. This network, shown in FIGURE 6, consists of a constant-current generator 48 which places a constant amount of charge on an integrating capacitor 50 for each pulse from the receiving system. When the integrator reaches a preset level, shown as VR2 in waveform (*f*) in FIGURE 2, corresponding to a preset number of pulses received at the receiver 40, a comparator network 52 senses this voltage and shorts out the capacitor, clearing the integrator for counting again. The time required for the integrator to count, or build up a voltage to a given preset level is then proportional to the gamma-count rate received at the target-borne sensor system.

It is desirable to be able to obtain a voltage inversely proportional to the fastest time-to-count in a series of such counts for later data reduction since the time of the fastest charging of the capacitor 56 indicates the closest miss-distance. (By "later" is meant on the order of 100 milliseconds.) In order to provide this function, a number of operations occur simultaneously. First, the integrator 46 integrates the incoming pulses for a time dependent upon the gamma photon count rate. During the time that this integrator is collecting counts, a second function is being performed by a ramp generator 54, whose circuit is shown in FIGURE 7. This generator is developing a linear ramp of constant predetermined slope (constant-negative slope). This is done by discharging a capacitor 56 from a predetermined voltage level with a constant-current drain. The voltage on the ramp capacitor 56 provides, at the time that the integrator network reaches is present level, shown as VR1 in waveform (*g*) of FIGURE 2, the desired relationship between the count rate and a positive, storable voltage. The storage network 60 produces an output signal whose level is determined by the level of the ramp voltage, just prior to reset, which is dependent on the time-to-count to the preset number shown in waveform (*f*) in FIGURE 2. When the preset number of counts is received and the integrator is shorted, a pulse is generated which first samples the ramp voltage and stores that voltage in the storage network, and resets the ramp function also. The voltage on the ramp capacitor 56 at the time of reset is directly proportional to the gamma-count rate. This is illustrated by waveform (*g*) in FIGURE 2.

The ramp and integrator functional operation at the time that the integrator reaches its preset level VR2 may be explained in another way. A comparator 52 senses when the integrator 46 reaches this level and generates a pulse which activates a one-shot multivibrator 52*a* within the chopper-comparator network. This one-shot pulse serves three separate functions. The leading edge of the one-shot pulse is used to provide a signal to short the integrator 46 and also turn on a readout transistor 58, in FIGURE 8, which transfers the voltage on the ramp generator 54 at that time into a storage network 60, whose circuit is shown in FIGURE 8. This so-called gating transistor 58 turns off before the end of the functional one-shot pulse so that the trailing edge of the pulse can be used to reset the linear ramp to its initial peak voltage. The typical pulse width for the triggering one-shot pulse is 50 microseconds, the gate transistor 58 which transfers the voltage from the ramp generator 54 to storage network 60 is typically opened for 20 to 30 microseconds. In this way, the storage capacitor 56 continually sees the last voltage on the ramp before it resets to its original value. Thus, during a missile pass, this storage voltage will rise in a step fashion, as shown by waveform (*h*) in FIGURE 2, and will hold at the maximum voltage level seen at the base of the ramp, shown in waveform (*g*), the maximum level being proportional to the instantaneous sampled gamma-count rate.

In order to provide ease of calibration and help eliminate noise from the system, an automatic reset function has been provided in the ramp generator 54. When the voltage on ramp capacitor 56 reaches a given preset discharge level, a signal from the comparator circuit 52 is generated which operates the functional one-shot multivibrator 52*a*, thereby shorting or resetting the integrator 46, transferring the instantaneous ramp voltage to the storage network 60, and resetting the ramp generator 54. Thus, if the gamma-count rate is so low that the integrator does not reach the preset level before the ramp reaches its bottom point, the system is reset and a new sample is taken. The ramp incline or slope is adjustable for calibrating voltage amplitude with miss-distance, as will be explained later. However, this ramp voltage never goes below VR1 in waveform (*g*). If, however, the gamma-count rate reaches a point that the integrator upper level VR2 is reached before the ramp reaches its automatic reset point VR1, the presence of a radioisotope within the scoring range of the system is indicated. At that time, the following functions occur: When the count rate reaches such a level that the system is reset by the comparator network 52 rather than the automatic ramp reset function in ramp generator 54, a pulse is generated with-

in the comparator 52 which passes to the missile pass detector 62 which starts a time delay. The time preset into this time delay is arbitrary but is made long compared to the time required for the slowest anticipated missile to pass through the largest anticipated scoring sphere. During this time, the storage network 60 sees a series of step increases in the bottom ramp voltage as the missile approaches. This is shown in waveform (*g*). At the end of this time delay, it is assumed that the missile has passed through the maximum and is progressing away from the target and the count rate is decreasing. Therefore, the storage network is at its peak, as shown in waveform (*h*). This time delay is typically 150 milliseconds.

If, and only if, voltage VR1 in waveform (*g*) is not reached by the time the predetermined voltage VR2 in waveform (*f*) is reached, the time delay is activated. At the end of this time delay, a pulse from the missile pass detector 62 is generated which starts a clock 69 in FIGURE 12, running at a calibrated 1 kc. rate. This clock drives a decimal readout network in the digital display 70, to be described later. This pulse also actuates the function generator 68. This function generator is a series of linear voltage ramps calibrated to approximate an inverse parabolic shape, such as is shown in FIGURE 3. The slope of each linear ramp and the break points (the point where the slopes of the linear ramp changes) have been calibrated to coincide with the 1 kc. counter 64 which is running. During the time that this function generator 68 is operating and the counter 64 is counting, the instantaneous voltage on the function generator 68 is being compared with the voltage in the storage network 60. At the time that the two voltages are equal, the counter is stopped and the function generator is reset to its stand-by value. In this fashion, the square root of the storage network voltage is taken and the number of pulses from the 1 kc. clock is exactly equal to the missile miss-distance.

The display network consists of two decades of standard silicon control rectifier (SCR) ring counters 72 with the second decade depending on a pulse from the tenth SCR in the first decade for its counting pulse. The 1 kc. generator described earlier is the counting pulse for the first decade. These SCR's have as their load in the circuit a 28-volt light bulb which provides the illumination to display the proper number. The display units, including the lights for illuminating the characters, are produced by Interstate Electronics Corp., North Hollywood, California.

One of the novel circuits of the system is shown in FIGURE 4. This is the circuit diagram of the high speed one-shot multivibrator 28 in the target-borne system. A positive current pulse is coupled through capacitor 80 causing tunnel diode 82 to exceed its peak point current and enter its negative resistance region. Tunnel diode 82, previous to application of the pulse, is biased in a low voltage state. The duration of time that the tunnel diode is held in this negative resistance region is determined by the size of inductor 84. When the current pulse from capacitor 80 reduces to zero and the voltage across inductor 84 then returns to zero, tunnel diode 82 returns to its original state. Pulse height from tunnel diode is on the order of 50 millivolts; too small for operation of circuitry in the next stage of the system. The base of transistor 84 is biased from a highly regulated 6-volt supply just slightly above the biased base of transistor 86 and therefore transistor 84 conducts. When the pulse from capacitor 80 causes the tunnel diode 82 to enter the high voltage state, the voltage at the base of transistor 86 exceeds that of the base of transistor 84 and transistor 86 then begins to conduct. A pulse is then generated of much greater magnitude than that resulting from the tunnel diode itself and a great deal of gain is effected. This one-shot circuit takes advantage of the extremely high frequency capabilities of the tunnel diode one-shot and still provides sufficient keying and stability to operate circuitry in the system. The one-shot multivibrator 32 in FIGURE 5 is functionally the same as the one just described.

Another important feature of this invention is the missile pass detector 62 which may be termed the "when" circuit. It produces a signal to tell comparator 52 and square function generator to operate after the missile has passed so that the closest point may be read out. The time delay provided by detector 62 tells the system when to read out and thus serves to produce a signal indicative of the closest point, which is the basic function that the entire system is to perform. The operation of missile pass detector 62 may be better understood with reference to FIGURE 6, showing the circuit diagrams of multivibrator 44, integrator 46, and the comparator and ramp reset 52. Transistors 90 and 92 comprise a comparator, one side of which samples the incoming integrator voltage from capacitor 50; the other side of the comparator is biased at a regulated six volts. Transistor 94 is biased such that its emitter looks at the plus six volts and its base looks at the ramp voltage from terminal J6 with a drop of approximately 7/10 of a volt through diode 96. When the ramp voltage reaches a point designated the automatic reset point, transistor 90 becomes forward biased, and current flows through its collector. This current flows into the base of 98 which has been biased in an off condition and it begins to conduct; thereby triggering the functional one-shot pulse described earlier. This functional one-shot pulse shorts the capacitor in the integrator 46, opens the storage gate transistor and resets the ramp. No readout is effected. When the count rate reaches a level such that the comparator senses that the base of transistor 90 is biased higher than the base of transistor 92, before transistor 94 conducts, a condition exists that a missile is approaching the sensor. Transistor 90 then begins to conduct and transistor 92 turns off, coupling a pulse through pin T6 to the time delay in FIGURE 11. Thus, only when the integrator level reaches the preset value before the ramp reaches its automatic reset point, then and only then does a pulse generate from the pass detector to affect a readout. All other times, the integrator is shorted, the ramp is reset and held in a steady state fashion and no readout occurs.

Another unique feature of the present invention is the case of calibration of the system to accommodate radiation sources of different strengths. Calibration is affected in the following manner: A radioactive tag which is equal to that tag to be mounted on the missile is placed a specified distance from the sensor at some time prior to the mission time. The miss-distance computer is set on an automatic position 100 by a switch on the front panel of the unit. Also provided on the front panel is a potentiometer 102. This miss-distance indicator samples the count rate, extracts the actual miss-distance, displays for a few seconds a readout of this distance, resets the system, counts again and displays the information again. This operation is controlled by the Readout Display Control and Reset Network 104 shown as the unijunction transistor timer network in FIGURES 12 and 14. During the time that the system is automatically displaying, adjustment of the front panel potentiometer 102 will adjust the miss-distance readout until the system continually reads out the proper range within the statistical accuracy and confidence levels specified. A single calibration point, that is only one position of the tag, is sufficient to provide calibration for the entire range of the scoring sphere. Once this calibration has been effected, the system is set on a manual mode and the operation can be commenced. In the manual mode, once a missile has passed and the distance readout in accordance with the calibration sampling, the display will hold this miss-distance information until released by a push-button 106 located on the front panel and operated by the observer. The adjustment of the potentiometer on

the front panel during calibration simply changes the slope of the linear ramp function. As this slope is changed for a given count rate from the radioisotope, the final voltage on the ramp function at the time that the preset voltage is obtained on the integrator changes. Thus, if the slope is increased without moving the position of the radioisotope from the sensor, the final voltage on the ramp for storage is less than for the previous value of slope. When the function generator then is activated, it runs for a longer time before the voltage on the function generator equals that voltage which has been stored. Therefore, the counter runs for a longer time and a higher number is read out on a digital display. If the slope is decreased, the voltage in the storage network will be higher, the counter will run for a shorter time and the readout will display a smaller number. Thus, if the system has been previously calibrated for one tag strength and a stronger tag is placed at the same range, the system will read out a smaller number and the slope must be increased on the linear ramp in order to readout the proper range. If a smaller tag is used, the slope must be decreased in order to read out properly. The function of the potentiometer in the circuit merely changes the rate at which the current is drained from the ramp capacitor; thus changing the slope of the linear ramp.

If errors in the system readout due to the velocity of the missile are too large to be acceptable, the following biasing technique can be employed: The above description of the system calibration shows that a change in the slope of the linear ramp function affects a linear change in the system readout. Therefore if an error in range due to velocity is known, and it is required that this be eliminated prior to the firing, the system can be calibrated with a radioactive tag to read proper ranges and then a fixed change can be effected in the slope to compensate for this linear error induced by missile velocity. This can be done with the present system because of the fact that the error due to velocity is nearly a constant for any missile range. If it were not, a linear change in the ramp function slope would not compensate completely, but would only compensate at some point. This biasing technique can be implemented with a three-position switch. For example: the first position would be the calibration point; the second position would bias the ramp for medium approaching velocities; and the third position for high approaching velocities. This would enable the operator to maintain the velocity error below some preset level for any missile attack pattern.

While I have herein shown and described certain specific details for the purpose of illustrating the underlying principles of this invention and its application, it is to be understood that variations and modifications therefrom will occur to those skilled in the art and that such departures are intended to be within the spirit of the invention as claimed.

What is claimed is:

1. A miss-distance indicator system for detecting the proximity of one object to another, comprising:
   (a) a source of gamma radiation positioned on one object;
   (b) radiation detection means on the other object, said detection means developing electrical pulses in response to gamma radiation received thereby; circuit means for producing pulses of constant height and width from said detection means pulses;
   (c) means integrating said circuit means pulses to a preset voltage level;
   (d) means for measuring the time of integrating said circuit means pulses to said preset voltage level; and,
   (e) means for converting such time interval measurement into separation distance information.

2. A miss-distance indicator system for detecting the proximity of a missile to a target, comprising:
   (a) a source of gamma radiation on said missile;
   (b) radiation detection means on said target, said detection means producing electrical pulses in response to said radiation; circuit means for producing pulses of constant height and width from said detection means pulses;
   (c) means integrating said circuit means pulses to a preset voltage level;
   (d) means for measuring the time of integrating said circuit means pulses to said preset voltage level; and,
   (e) means for converting such time measurement into separate distance information.

3. A distance indicating system for indicating distance to a pulse producing target comprising:
   (a) means for receiving pulses;
   (b) means for counting a predetermined number of said pulses;
   (c) means for measuring the time interval required to count said predetermined number of pulses, whereby said measurement is inversely proportional to the square of the distance to said target;
   (d) circuit means for converting said measurement into an electrical signal directly proportional to the distance to said target, said circuit means including,
      means generating a sawtooth voltage waveform of uniform peak height and of uniform declining slope,
      means storing voltage pulses of amplitude determined by the sawtooth voltage waveform height at the end of said time measurement,
      means generating a square function voltage and comparing said square function voltage with the voltage of said stored voltage pulses,
      means for measuring the time required to equate said voltages,
      means for converting said equating time measurement to an electrical output signal; and,
   (e) readout means for converting said output signal to distance information.

4. A missile distance indicator system for detecting the closest proximity of a missile to a target comprising:
   (a) a source of gamma ray radiation of known activity;
   (b) radiation detection means developing an electrical signal pulse in response to each received gamma ray;
   (c) means for counting a predetermined number of said pulses;
   (d) means for selecting the shortest necessary time interval for receiving a sufficient number of said gamma rays to produce said predetermined number of said pulses;
   (e) means for measuring said time interval selected by said time selecting means;
   (f) means for converting said time measurement to distance information;
   (g) said time selecting means including means for providing a voltage analog of a missile approach to the target, and means integrating said voltage analog and storing the resultant voltage whereby the maximum voltage amplitude represents the shortest distance of said missile from said target; and,
   (h) said time measurement means including means for generating a declining function voltage, means comparing said voltage amplitude and said function voltage amplitude, and means noting the time interval required for said function and stored voltages to become equal.

5. A miss-distance indicator system as in claim 4, including a missile pass detector means for sensing the approach of a missile; and,
   means starting the comparison of stored and function voltages a predetermined time delay thereafter.

6. A missile distance indicator system as in claim 4 wherein the means converting time interval information into distance information comprises counter means generating pulses from the starting time for the comparison of said voltage amplitudes until said voltages are equal; and,

a display system that sums the number of pulses thus counted and displays them in numerical form.

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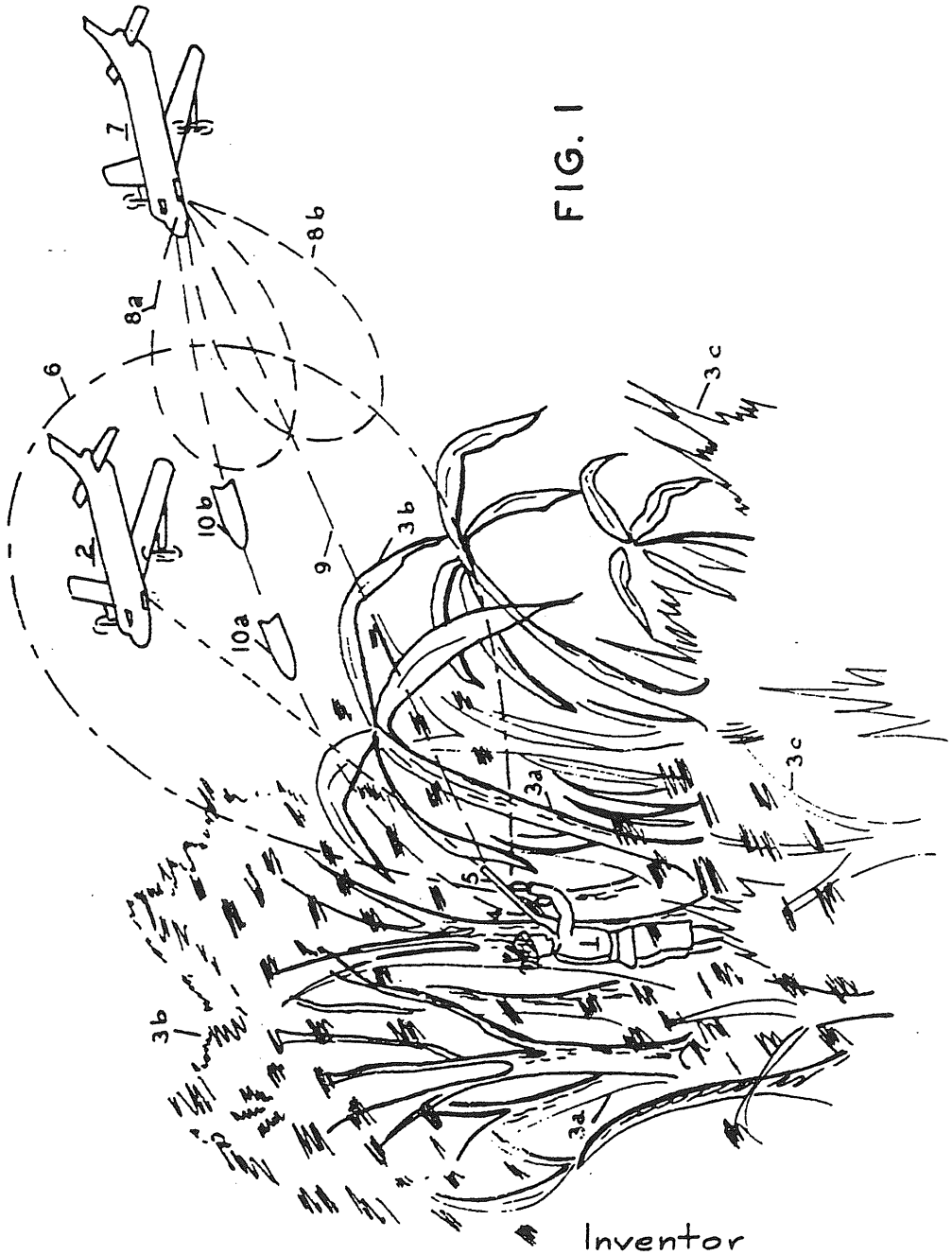
JAMES W. LAWRENCE, RALPH G. NILSON, *Examiners.*

Dec. 19, 1967 H. R. CHOPE 3,358,602

METHOD AND APPARATUS FOR DETECTING AND IDENTIFYING REMOTE OBJECTS

Filed June 25, 1964 6 Sheets-Sheet 1

FIG. 1



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Dec. 19, 1967 H. R. CHOPE 3,358,602

METHOD AND APPARATUS FOR DETECTING AND IDENTIFYING REMOTE OBJECTS

Filed June 25, 1964 5 Sheets-Sheet 2

FIG. 2

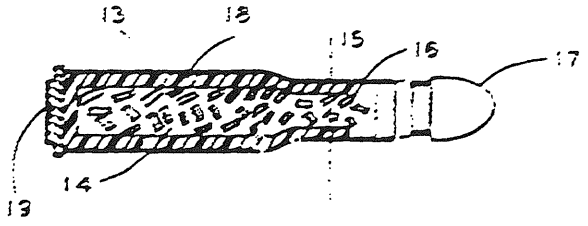

FIG. 3

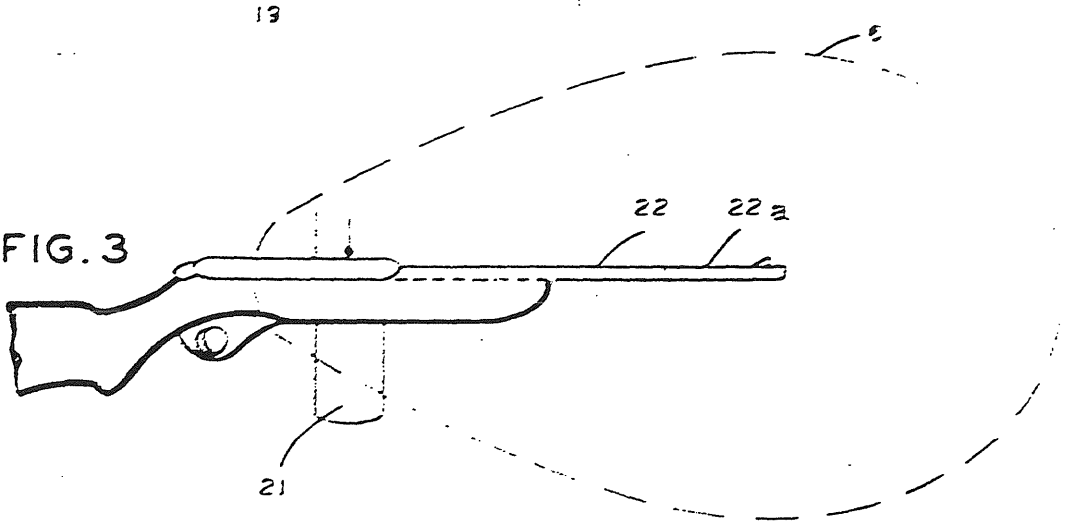

FIG. 4

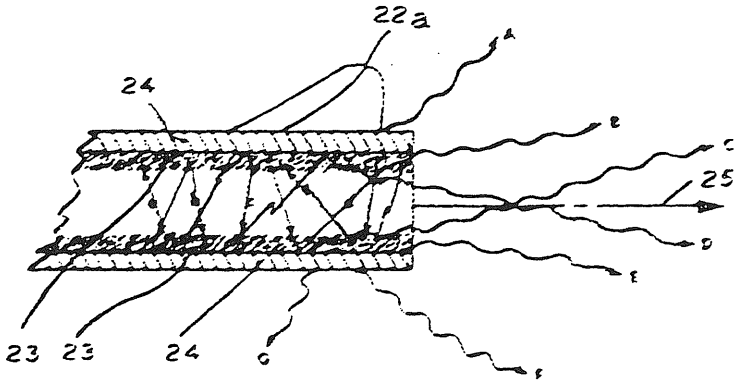

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FIG. 5

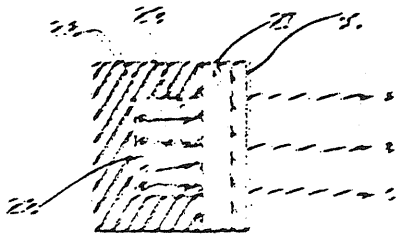


FIG. 6

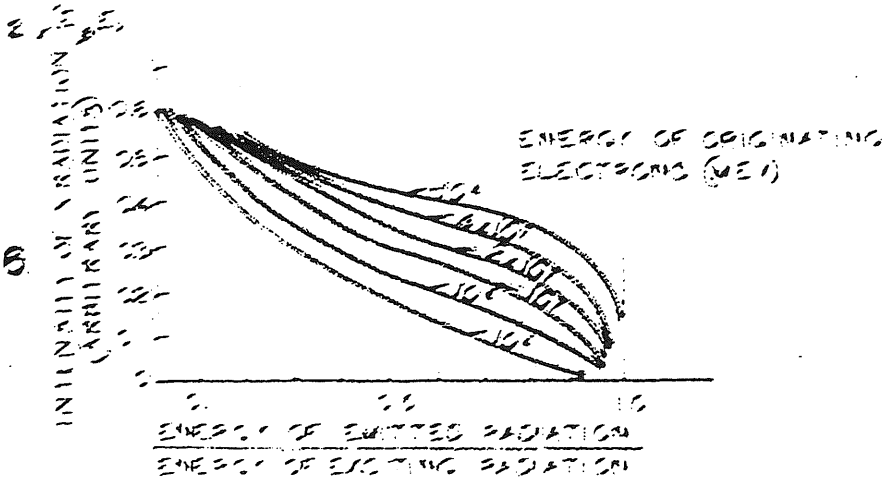
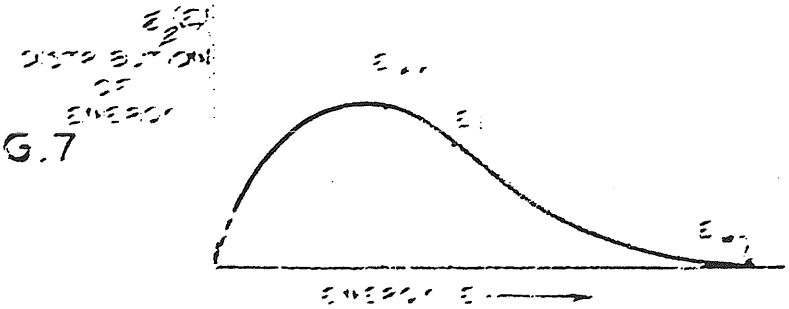
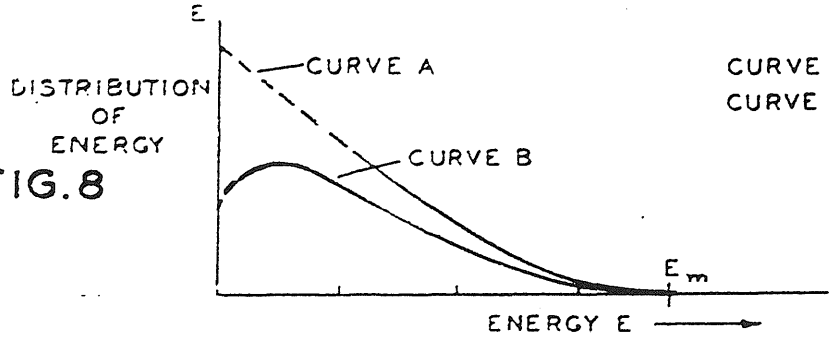


FIG. 7





CURVE A - NO FILTER
CURVE B - WITH FILTER

FIG. 8

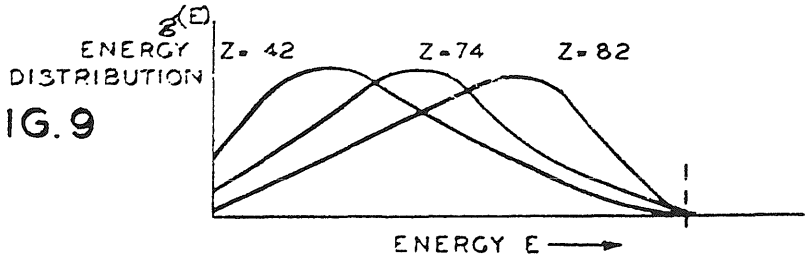


FIG. 9

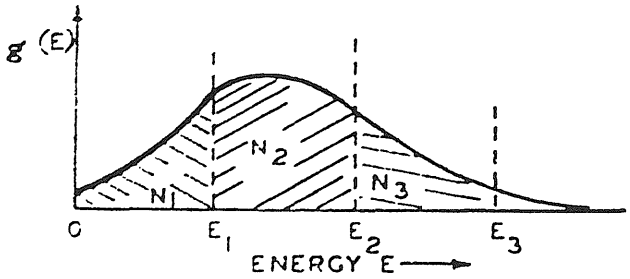


FIG. 10

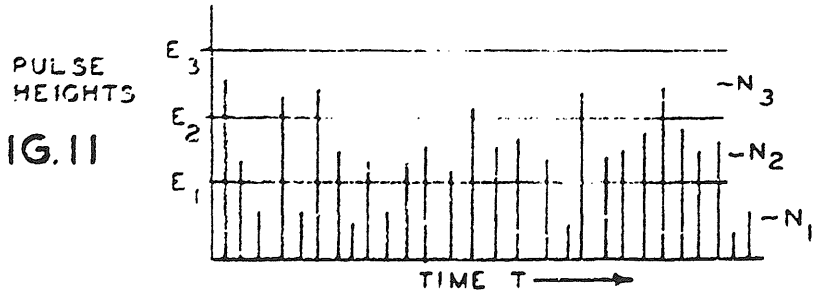


FIG. 11

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FIG. 12

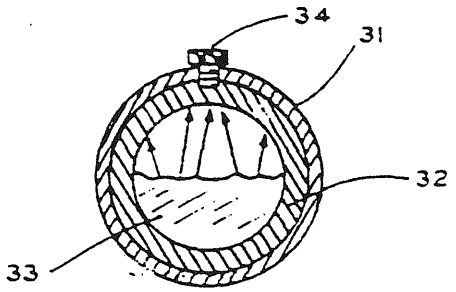


FIG. 13

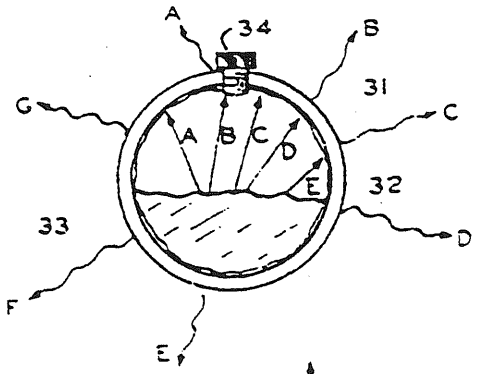
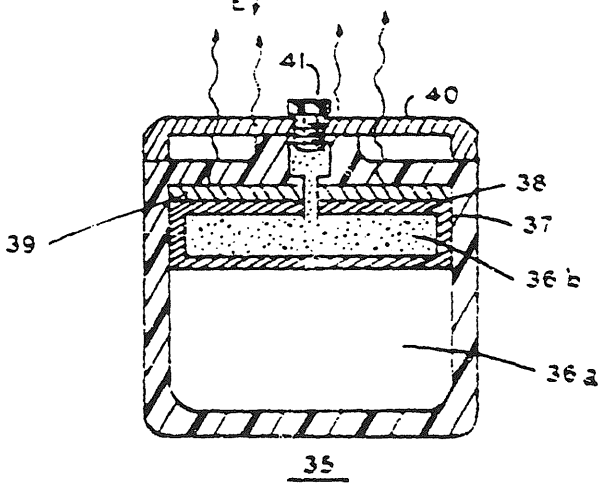


FIG. 14



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such uses are described in the following co-pending patent applications assigned to the same assignee as the present invention: Ser. No. 271,153 filed Apr. 8, 1963, by Henry R. Chope for "Nuclear Indicating System"; Ser. No. 271,154 filed Apr. 8, 1963, by Henry R. Chope, Leonard C. Brown and William R. Clare for "Indicating System"; Ser. No. 271,342 filed Apr. 8, 1963, by Angelo J. Campanella for "Nuclear System"; and Ser. No. 272,182 filed Apr. 8, 1963, by John J. Lentz for "Nuclear Measuring System."

A brief description of one such nucleonics missile tracker is also given in the May 4, 1964, issue of "Missiles and Rockets" magazine. In this system, a high energy gamma source is mounted at one end of a missile. The source emits two energies, one at 1.17 mev. and one at 1.33 mev. Ground-based directional trackers at two or three stations are caused to point toward the source and, hence, toward the missile, thus yielding azimuth and elevation angles.

Nucleonics tracking systems possess certain advantages over radar and other microwave systems in that they can be designed to experience little or no problems with propagation. These systems thus provide an all-weather capability for tracking since they are neither affected by "heat shimmer" common to optical systems nor multipath transmission and ground clutter aberrations common to radar. The gamma particles detected travel in a straight line from the source of the detector; scattered or secondary gamma photons are discriminated against by a collimator at the detector and by electronic discrimination.

Actual tests conducted with airborne, sensitive radiation detectors indicate that identifiable signals and directions can be obtained at slant ranges of approximately 3000 feet for sources emitting energies at 1.33 mev. maximum energy. The detectable range of a nucleonics system at ground level depends upon the energy of the emitting source and its quantity (or amount). The more energetic sources possess higher penetrating power. The greater the quantity of source utilized, the greater the detectable signal at a given range compared to radiation background.

The nucleonics ranging and identification systems discussed above are cooperative systems in that the radiating source of energy is willfully and cooperatively located at a given place so as to provide a signal. Such nucleonics systems provide certain advantages over competing microwave, radiofrequency, or optical systems. Among these advantages are:

(1) The source of energy is self-powered and requires no external source of electrical energy;
(2) A particular radiating source can be positively identified in terms of its energy spectrum;
(3) The source of radiant energy can be made small and extremely lightweight;
(4) The system is silent beyond some maximum range and does not provide a "telltale" signal subject to electromagnetic monitoring at large distances;
(5) In certain source systems, the radiation can be "turned on" or "turned off," depending upon activating conditions; and
(6) The radiating source can be caused to be extinguished, after which time there remains no detectable radiation.

My invention takes advantage of these desirable characteristics in a unique method and apparatus which will first be described in connection with a system for locating and identifying a particular type of weapon in the hands of an enemy.

Description of a weapon locating and identifying system

In the system pictorially represented in FIG. 1, a concealed enemy soldier 1 attempts to attack low-flying aircraft 2. The enemy soldier may be well-concealed by trees 3*a*, foliage 3*b*, and other terrain objects 3*c* which cause visual detection of his position to be difficult. However, after firing weapon 4, the metallic rifle barrel 5 is excited by deposited beta emitters and yields a radiation pattern similar to that outlined by the dashed line 6.

It can be seen from FIG. 1 that radar or microwave detection of the enemy equipment or weapons would also be extremely difficult. Objects such as trees 3*a* and foliage 3*b* would yield strong echoes. Since the aircraft is flying at extremely low altitudes (often as low as 100 feet above the ground), radar detectors within the aircraft would receive a large amount of ground clutter. The protecting objects and ground clutter would tend to obscure radar signals obtained from the enemy's equipment. However, when the rifle barrel 5 becomes radioactive, the high energy photons emitted from the barrel penetrate the foliage and provide a radiation pattern whose relative intensity is indicated by the dashed outline 6.

An attack aircraft 7, fitted with directional and ranging radiation detectors, is also shown in FIG. 1. Two detectors provide "up" and "down" signals. These detectors (not shown) may be constructed in accordance with the principles set out in the aforesaid co-pending applications. The difference between these signals provides angle direction in the vertical plane perpendicular to the surface of the earth. Two other detectors similarly provide "left" and "right" signals. The difference between these signals provides azimuth angle information to the location of the radiating target, which, in this case, is the position of the hostile soldier. Relative receiving lobes in the vertical plane are indicated by 8*a* and 8*b* in FIG. 1. When the signals received from both vertical (up-down) detectors 11 are equal, the system axis indicated by dashed line 9 is pointed directly toward the radiating target. Deviations in signal may be read out on a meter within the cockpit of aircraft 7 to provide the pilot of the aircraft with information as to when to drop a destroying missile such as a napalm bomb. Two such destroying missiles are indicated at 10*a* and 10*b* in FIG. 1.

As will be more fully described hereinafter, the readings from the two vertical and two horizontal detectors are also summed and fed to an energy discriminating circuit within the electronic circuits of the directional detector. This circuit then reads out the energy-identifying spectrum of the radiating source. This readout then provides an identification of the original isotope and weapon that is being utilized by enemy soldier 1.

As is well known, the time of dropping bombs or missiles 10*a* and 10*b* to assure the maximum probability of destruction depends upon (1) the speed of the aircraft, (2) the vertical and horizontal angles to the target, (3) its distance from the target, and (4) the altitude of the aircraft. The distance from the target can be determined by a measurement of the intensity of the integrated signals from the four radiation detectors.

FIG. 2 illustrates a cutaway section of a rifle cartridge suitable for use in the system of FIG. 1. The cartridge 13 is an ordinary cartridge as would be used in a rifle, carbine, or automatic firing weapon, except that some of the individual pellets of smokeless powder 14 contain a beta-emitting isotope. In the cross-section view shown here, individual pellets 14 which are made radioactive are shown to the left of line 15. In order to make difficult the detection of the modified cartridges, pellets 16 shown to the right of line 15 are not radioactive and hence are ordinary pellets of smokeless powder required for the particular caliber of bullet 17 used by the cartridge.

Various methods may be used for imbedding the beta-emitting isotope into the individual smokeless powder pellets. One method causes the beta-emitting isotopes to be added to the smokeless powder pellets during their manufacturing process. A metered amount of beta-emitting isotope is mixed into the smokeless powder slurry prior to the extrusion of the individual pellets. The outer case of the cartridge 13 is of conventional design. However, lining this case is a sleeve 18 of low-Z combustible plastic

material. As will be more fully described hereinafter, the combination of self-absorption shielding within the individual pellets and the shielding sleeve 18 absorbs substantially all the beta radiation within the unfired cartridge. This combination shielding-absorber prevents the formation of beta-excited X-rays within the copper cartridge 13 or the bullet 17. Soft X-rays formed within the smokeless powder pellets are substantially absorbed by the plastic sleeve 18, the cartridge 13, the bullet 17, or the firing cap 19.

FIG. 3 is an outline drawing of a rifle or automatic weapon as might be used in combat. Dashed outline 6 again illustrates the radiation field formed with respect to the radiating rifle barrel when the weapon is fired. In the operation of my invention, the cartridge illustrated in FIG. 2 is loaded into magazine 21. When the cartridge is fired, the residual combustion products caused by the burning of the smokeless powder pellets stick to the inner walls of the gun barrel 22. This coating of combustion products is rich in beta-emitting isotopes. The beta rays obtained from the isotopes then activate the gun barrel, causing it to be radioactive and producing a field of X-ray photons.

This action is illustrated in greater detail in FIG. 4 which shows a partial cross section of the end 22*a* of the rifle barrel. Combustion products 23 stick to the inner walls of the gun barrel 22*a*. In some applications of this invention, it may be desirable to have an adhesive compound mixed with the smokeless powder pellets, thereby causing the beta-emitting combustion products 23 to adhere more firmly to the inner wall of the gun barrel. The paths of the beta particles are illustrated schematically by lines *a*, *b*, *c*, and *d* within the gun barrel. As the beta particles traverse the various paths and strike the metallic wall 24 of the rifle barrel 22, the high-speed beta particles are decelerated and a fraction of their energy is converted in known manner to X-ray photons. These photons travel in various directions away from the gun barrel, as indicated in FIG. 4 by wavy lines A, B, C, D, E, F, and G, providing the integrated radiation pattern 6 of FIGS. 1 and 3. The direction of a particular gamma photon may be at any angle with respect to the incident beta ray. However, for beta particle energies greater than 2 mev. (million electron volts), the direction of maximum radiation intensity tends toward the forward direction of the original beta particle. Due, however, to the absorbing effect of the gun barrel wall 24, the maximum radiation pattern would be along the axis of the gun barrel, indicated by the dashed arrow 25 in FIG. 4.

It will thus be seen that, in the system just described, the enemy himself unwittingly broadcasts his location and identifies himself by firing a particular weapon and ammunition. An important advantage of my invention is the fact that these cannot readily be identified, in advance of firing, even by sensitive nuclear detection techniques. Thus, this system is far superior to prior-art radio-beacon systems that have heretofore been proposed for such purposes; for example, small radio transmitters or transponders concealed within gunstocks or other portions of enemy materiel. Any such radiofrequency electromagnetic devices of sufficient radiating power to permit remote tracking are relatively easy to detect by electronic countermeasures equipment commonly accompanying military troops.

In contrast, the beta-excited X-ray sources of my invention remain dormant and nonradiating within the weapon or other piece of materiel until triggered into action. Since in many areas of limited warfare, a large amount of enemy equipment is that which is appropriated through enemy action, the dormant transmitting apparatus or beacon is deliberately implanted within equipment for which there is a high probability it will fall into enemy hands.

A better understanding of the principles underlying this invention can be obtained by now examining in greater detail some mechanisms for obtaining beta-excited X rays.

Theory of beta-excited X radiation

In ordinary X-ray tubes, for example, as utilized in medical practice, X radiation is generated by electrical means. Electrically produced X rays are obtained by causing an accelerated electron to strike an X-ray target. In an X-ray tube, electrons are conventionally obtained from a thermionic, heated cathode and are accelerated through an electrical potential applied between the cathode and the target. When a particular electron strikes or impinges upon the target, part of its energy is converted to X radiation. The maximum frequency of the X-ray photon created can be obtained from the following:

$$E_e = h\nu_{max.}$$

where E_e is the energy of the exciting electron, h is Planck's constant, and $\nu_{max.}$ is the maximum frequency of X radiation. Only a small fraction of the energetic electrons have all their energy converted to X radiation. The other electrons lose part of their energy by other mechanisms, such as ionizing collisions within the target before their remaining energy is converted to that of X radiation.

In the practice of the present invention, a beta particle emitting material is used as the source of high-speed electrons. Beta particles are high-speed electrons obtained from beta-emitting substances and hence may also be directed against a suitable target material to generate X rays. Beta-excited X rays possess many advantages over the electrically produced X rays. First, bulky electrical equipment is not required to provide the "beam of electrons" and accelerating voltages. Secondly, beta emitters can be simply shielded. For example, approximately ¼ inch thickness of the plastic material sold commercially under the trademark "Plexiglas," an acrylic resin material manufactured by Rohm & Haas, Philadelphia, Pa., will shield all beta particles from a 2.16 mev. emitter.

FIG. 5 shows the basic parts of a beta-excited X-radiation source. Lining wall 26 is the container or housing for the beta emitter. It is constructed of a material of low atomic number (Z). A cover plate 27, constructed of a material with a high atomic number (Z), forms the X-ray target. The enclosed space 28 contains the beta-emitting substance. The physical state of the beta emitter may be gas, liquid, or solid. Lines *a*, *b*, *c*, and *d* represent schematically some paths of beta particles impinging on target 27. Target 27 may be constructed of different materials and have various shapes. Generally, the higher the atomic number of the target material, (1) the more energetic or penetrating the X radiation and (2) the greater the conversion efficiency of the beta particles to X-rays.

Dashed line 29 in FIG. 5 illustrates that in some cases a partitioning member of low-Z material may be interposed between the beta-emitting material and the target 27 so that initially the target 27 is shielded from the beta particles, thereby preventing the generation of penetrating X radiation. In one embodiment of my invention, described in greater detail at a later point in this specification, the partitioning material 29 is gradually removed through a self-dissolving or corroding action within the material so as to "turn on" the radiation at some specified time.

Also shown in FIG. 5 is an X-radiation filter or screen 30 against the outside face of target plate 27. Its function, as is well known in the art, is to shape the resulting X-ray spectrum by "screening out" soft X rays. It may also be utilized to shape the beam pattern of the X-ray source in known manner.

The resulting X-ray spectrum obtained from a system as shown in FIG. 5, represented schematically by wavy lines A, B, C, is a complicated function of the spectrum of beta energies and the construction of the structure. It depends upon (1) the energy spectrum of the beta ex-

citer in space 28, (2) the atomic number, thickness, and shape of the target material 27, and (3) the atomic number, thickness, and shape of the screen or filter 30. For more detailed descriptions of beta-excited X-ray sources of various types and designs, reference may be made to U.S. Reissue Patent 25,353, granted Mar. 19, 1963, to George B. Foster and Walter H. Canter, Jr., and titled "Radioactive Thickness Gauge"; also to U.S. Patent No. 2,999,935, granted Sept. 12, 1961, to George B. Foster and titled "Convertible Radiation Source." These patents explain in some detail various means and mechanisms for obtaining X-radiation sources of differing characteristics.

The energy of the X radiation produced by electrons through collisions with atoms of a target may be of any value up to the energy of the originating electrons. H. A. Bethe and W. Heitler, in the "Proceedings of the Royal Society," vol. A146, page 83 (1934), have given formulas which, when applied to a continuous spectrum emitter and a thick target, yield an expression for the X-radiation output of an excited target. These formulas are complicated and are found to supply energy spectra which only approximate measured results. A better determination of the performance of an actual X-radiation source system can be obtained from a consideration of graphical energy distribution functions. These may be combined according to certain analytical expressions to yield a resulting energy distribution function for the final X radiation which is in close agreement to that actually measured.

FIG. 6 is a graph showing the energy distribution of emitted radiation for various energies of the originating electrons. It can be seen that as the energy of the originating electron increases, there is a greater probability that the X radiation will have an energy which approaches that of the originating electrons. Each of the curves in FIG. 6 can be considered as an energy distribution function

$$g_x(E)$$

for the X radiation resulting from electrons of a specified energy. There is a particular distribution function for each energy of exciting beta particles.

FIG. 7 is another graph showing the spectrum of beta particle energies obtained from a particular beta emitter. This spectrum is a continuous spectrum extending from energies near zero through some maximum energy E_m. The average energy, E_{av}, is often considered to be approximately one-third E_m. Any single beta energy, such as E_1 in FIG. 7, gives rise to a continuous spectrum of X-ray energies up to a maximum energy of E_1.

A resulting X-ray spectrum can be obtained from curves as shown in FIGS. 6 and 7 by a convolution operation of the distribution functions of energy indicated in each curve. The convolution operation is a reasonably straightforward one to grasp and understand and is explained in many books on mathematical analyses. A particularly understandable discussion of convolution is that given in "Notes on Analog-Digital Conversion Techniques" by Alfred K. Susskind, published by The Technology Press, MIT, 1957, pp. 210–222.

The convolution operation provides a composite distribution function by causing one distribution function, such as $g_x(E_\beta, E)$, to be scanned by another, such as $g_\beta(E)$. The composite function $g(E)$ is obtained mathematically as follows:

$$g(E) = \int_0^E g_x(E_\beta, E')g_\beta(E-E')dE' \quad (1)$$

In this expression, E' is a variable of integration. With this notation, E is regarded as a summation of increments in E' between $E'=0$ and $E'=E$, such that

$$E = \int_0^E dE' \quad (2)$$

Symbolically, the convolution of the two functions is often indicated as follows:

$$g(E) = g_x(E_\beta, E) * g_\beta(E) \quad (3)$$

The symbol * indicates the convolution between the g_x and the g_β functions. Note that the g_x function is written as

$$g_x(E_\beta, E)$$

In this expression, E_β is a parameter for the convolution operation at each beta particle energy.

The convolution method provides a powerful mathematical tool for obtaining complicated resulting functions by a combination of graphical and analytical methods. The mathematical operation of convolution can be performed by a graphical integration, or if a digital computer is available, a numerical integration can be quickly made.

FIG. 8 illustrates the energy curves obtained from beta-excited X-radiation sources. Curve A in FIG. 8 represents a spectrum without filtering out the softer or lower penetrating X-ray photons. Curve B represents the resulting output after filtering by a screen of proper material and shape.

FIG. 9 illustrates three X-ray spectra normalized to the same maximum amplitude for targets of similar shapes and thicknesses but of different Z numbers. Here it will be seen that the maximum energy peak is shifted to higher energies as the Z of the target is made larger. Thus, it is possible to obtain "spectral signatures" of different excited sources by knowing the material of the target. Likewise, but not shown here, a different mix of exciting beta particles will cause a shift in the maximum energy peak. The higher the energies of the beta exciter, the more the peak of the resulting X-ray spectra is shifted toward higher energies.

FIG. 10 illustrates a particular X-ray spectrum. If the radiation detector counts and resolves individual pulse heights, then the numbers of counts occurring between successive energy levels would be proportional to the areas N_1, N_2, and N_3 found under the different parts of the curve in FIG. 10.

FIG. 11 illustrates the distribution of detected pulse amplitudes in the time domain. The relative number of pulses found in each energy band (or voltage level in the associated electronics) is proportional to the areas N_1, N_2, and N_3 of the curve in FIG. 10. That is, the area N_1 represents the relative number of counts found between the energies 0 and E_1; the area N_2 represents the relative number of counts found between the energies E_1 and E_2; and the area N_3 represents the number of counts found between the energies E_2 and E_3.

Specific embodiments of radiating sources

In the earlier description of a specific locating and identifying system, the excited beta emitter was deposited onto the inner lining of a rifle barrel. Other containments of the exciting energy are useful, especially in cases in which a delayed time reaction is desired before a given piece of equipment is to start "broadcasting." Individual emitters may be concealed in various places of equipment; for example, within a particular mortar shell, under the hood of a vehicle, or somewhere within an integral part of a vehicle's engine.

FIG. 12 shows one form of a delayed action X-ray transmitter. It comprises an outer spherical container 31 of high-Z target material and an inner spherical lining shell 32 of low-Z material. The beta-emitting material is represented as a liquid within spherical volume 33, but it should be remembered that the state of the beta emitter can be either solid, liquid, or gaseous. A particularly desirable form of beta emitter is gaseous krypton-85. Kr-85 is a totally safe emitter. Since Kr-85 is an inert gas, it would not be taken into the body mechanisms even if swallowed.

In the embodiment of FIG. 12, the inner lining shell 32 also contains a delayed acting dissolving agent (not shown). After a period of time, determined by the relative amount of solid low-Z container shield and added solvent,

the container is dissolved or eroded away. Escape valve 34 is a valve which allows the beta emitter to escape on some time basis. The escape rate of the beta emitter (for example, a beta emitter in the gaseous state) can be controlled by the valve in such a manner that the X-ray transmitter will become totally inactive and not subject to monitoring beyond some set time.

FIG. 13 shows the condition of the X-ray transmitter of FIG. 12 after the inner liner 32 has been largely dissolved or eroded away. Beta particles, some of whose tracks are shown by the lines *a*, *b*, *c*, *d*, and *e*, now strike the outer target casing 31 and yield X-ray photons represented schematically by rays A, B, C, D, E, F, and G.

By way of illustration, a practical X-ray transmitter of this design can be built to have a total outer diameter of approximately ⅝ inch. Such small transmitters may be planted in numerous places and spots in various equipment subject to appropriation by the enemy.

FIG. 14 shows another embodiment of an X-ray transmitter. In this cross-section view, the emitter is placed within an ordinary component of a vehicle's engine, such as its distributor or oil filter cup 35. Volume 36*a* may contain the usual distributor elements or oil filter cartridge, as the case may be (not shown); while volume 36*b* contains the beta emitter, indicated here as a gaseous substance contained within housing 37. The upper wall 38 of the beta housing is caused on a time basis to dissolve or erode away, for example, by chemical attack in the same manner as the inner liner 32 in the transmitter of FIGS. 12 and 13. When this occurs, a high-Z target 39 becomes the radiating X-ray transmitter.

In FIG. 14, cap 40 represents the top of the distributor or oil filter cup. It could optionally be the target material 39, itself. For example, an iron cap is of suitable atomic number (Z) for use as an X-ray target. In another modification (not shown), a combination cap and target may be used, in which the active target material is laminated between layers of a phenolic material. Such would provide a usable cap for the top of an engine element, such as a distributor.

Element 41 shown in FIG. 14 is intended to represent either a screw securing the cap 40 or a gaseous escape valve, like the valve 34 in FIG. 12 for "turning off" the radiation after some prescribed time; or it may perform both these functions.

Beta-excited X-ray sources of the types I have described may be designed to be entirely stable and to present no hazards to operating personnel working around the equipment in which they are placed. Their basic design parameters are well known to those skilled in the art, since many thousands of beta-excited X-ray sources have been built for industrial uses. In addition to their safety and stability, they provide a great flexibility as regards to the quantity and energy spectrum of radiation available. Their novelty, as applied to the method and apparatus of the present invention, resides in their combination with means, such as I have just described, by which they can be selectively "turned on" or "turned off," after predetermined time intervals or upon the happening of specified events, and utilized to provide the telltale radiation pattern permitting their location and identification by remote radiation-measuring and tracking apparatus.

Another advantage of the sources of the present invention is that the actual targets yielding X radiation are active only so long as the exciting beta radiation is present. Hence, a given weapon or vehicle rendered temporarily active becomes totally inert, and undetectable by radiation-monitoring means, when the exciting beta emitter is removed.

The manner in which the activated radiation sources may be located and identified from a remote point will now be described in greater detail in conjunction with FIG. 15. FIG. 15 is a schematic block diagram of a nuclear detection and tracking system such as might be carried in the attack aircraft 7 of FIG. 1.

Nuclear tracking and electronics system

The nuclear tracking and electronics system has the functions of providing output data on: (1) the angular direction to a remote radiating source, (2) a measure of its distance, and (3) a spectral readout and recognition of the particular source's energy distribution characteristics. These functions may be performed with relatively simple radiation detectors and electronic circuits now to be described. FIG. 15 illustrates, in simplified block diagram form, those circuits of the nuclear tracking and electronics system for obtaining such output data in the vertical or elevation plane. Substantially identical circuits may be used to obtain simultaneous data in the horizontal or azimuth plane.

The circuits of FIG. 15 comprise a pair of radiation detectors 50, signal processing and amplifying circuits 51, and computing, indicating, and control circuits 52. The detectors may be one of several well-known types, e.g., scintillation detectors or lithium-silicon detectors. Assuming for the moment the plane of the paper to be vertical, the detectors 50 comprise an upper detector 50*a* and a lower detector 50*b* arranged to receive radiation 53 emanating from a remote source through slit collimators 54*a* and 54*b*, respectively. These detectors and collimators may, for example, be constructed and arranged in a manner shown and described in greater detail in the aforesaid co-pending application Ser. No. 272,182 of John J. Lentz. As is taught in the Lentz application, each collimator comprises a plurality of parallel plates transverse to the vertical plane of the detectors, much like the slats of a Venetian blind. The parallel plates of the upper collimator 54*a* are tilted upward at a small angle with respect to a coordinate center plane through the axis of symmetry 55 between the two detectors and their collimators; and the parallel plates of the lower collimator 54*b* are tilted downward at the same small angle with respect to this center plane. As is fully explained in the Lentz application, when the remote radiation source is located within the center plane, equal "UP" and "DOWN" signals U and D are generated in the upper and lower detectors and impressed on the upper and lower output lines 56*a* and 56*b*, respectively. When the remote source is located above the center plane, the signal U is greater than the signal D; conversely, when the source is located below the center plane, the signal D is greater than the signal U.

Both detector output signals, U and D, are fed to a subtractor 57 and an adder 58. These may comprise circuits well known to those skilled in the art of computer design, so arranged that the subtractor 57 yields at its output line 59 a difference signal proportional to the value $U-D$, and the adder 58 yields at its output line 60 a sum signal proportional to the value $U+D$. The signals $U-D$ and $U+D$ are fed to a divider 61 which also functions in well-known manner to produce a signal at its output line 62 proportional to the ratio

$$\frac{U-D}{U+D}$$

This ratio signal is a measure of the angular deviation of the remote source above or below the coordinate center plane (with respect to the upper and lower detectors). The operation of dividing the difference signal $U-D$ by the sum signal $U+D$ causes the ratio function to be essentially independent of range to the remote source, even though the actual received radiation intensity decreases as the range increases.

The ratio signal is fed to an amplifier 63 over line 62. The output of amplifier 63 then provides voltage information on the vertical angle between the coordinate center plane through axis 55 and a line drawn from the detector assembly 50 to the remote radiation source. This information is fed over line 64 to a cross-hair type of aircraft indicating instrument indicated schematically

SIGNAL PROCESSING AND
ANALYZING CIRCUITS
31
COMPUTING, INDICATING
AND CONTROL CIRCUITS
52
SPEED INPUT
ALTITUDE INPUT
HORIZONTAL ANGLE INPUT
51
54
12
73
74
75
77
78
13
76
SPECTROGRAM SIGNATURES INPUT

FIG 15

United States Patent Office

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3,358,602

METHOD AND APPARATUS FOR DETECTING AND IDENTIFYING REMOTE OBJECTS

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6 Claims. (Cl. 102—38)

The present invention relates generally to a method and apparatus for detecting and identifying remote objects, for example, the position and nature of enemy equipment and troops. More particularly, it pertains to an improved method and means for tagging, locating, and identifying enemy equipment and apparatus such as may be found in isolated geographical locations.

A defense activity receiving increasing emphasis is that of limited warfare. Such warfare may be fought anywhere on the globe and may often be characteristic of operations fought in jungle or other inaccessible terrain. Location and detection of enemy troops and equipment are difficult. Radar, sonar, and infrared locating and tracking systems all have serious operational limitations when used in jungle or guerrilla warfare. Effective countermeasures have also been developed for use against these types of systems. Further, in many areas of the world, a large percentage of the equipment, such as guns, mortar, and even vehicles, is that which has been appropriated or captured for conversion and use by enemy or guerrilla troops. Under such circumstances, it is even more difficult to distinguish between the equipment of troops on one side and that of troops on the other side.

In accordance with one embodiment of my invention, selected items of military materiel, for example, weapons, ammunition, or vehicles, are provided with one or more nuclear radiation-generating sources embedded or concealed therein. These sources are so designed as to be inactive, and virtually undetectable even by sensitive radiation-monitoring means, until they are "triggered" into action after a predetermined time interval or upon the happening of a predetermined event (such as the firing of a weapon). If such materiel is permitted to fall into the hands of enemy troops, either accidentally or according to plan, it can later be located and identified by nuclear tracking means, even at considerable distances. In accordance with my invention, it is also possible to design the sources so that several different radiation characteristics can be produced and identified at the remote tracking point, thereby distinguishing one type of captured or "planted" equipment from another.

It is therefore broadly an object of my invention to provide an improved method and apparatus for detecting and locating remote objects and positively identifying their source of manufacture or origin.

Another object of my invention is to provide an improved remote object locating and identifying system that is less vulnerable to defensive countermeasures than prior art systems.

Still another object of the present invention is to provide an improved method and apparatus for effectively detecting and identifying certain types of weapons and equipment utilized by enemy or guerrilla forces.

Another object of my invention is to provide an improved method and apparatus whereby weapons or other objects appropriated by the enemy will have imparted to them a "silent" radioactive tag which under some future action or event causes such weapons or objects to become active radiation transmitters of identification and location.

Another object of my invention is to provide a method whereby such tagged objects and enemy apparatus can be detected at a distance.

Still another object of my invention is to provide an improved system whereby enemy or hostile troops can be effectively located so that they may be engaged in combat.

Another object of my invention is to provide a positive identification system that will distinguish between materiel of friendly and enemy forces.

Yet another object of my invention is to provide a nuclear, remote-object detecting and locating system which remains inactive and virtually undetectable until activated upon the happening of a predetermined event or the lapse of a predetermined time.

For additional objects and advantages, and for a better understanding of my invention, attention is now directed to the following detailed description and accompanying drawings. The features of my invention believed to be novel are also particularly pointed out in the appended claims.

In the drawings:

FIG. 1 is a pictorial sketch showing how the invention may be applied to location of enemy personnel in jungle warfare;

FIG. 2 is a section elevation of a rifle cartridge containing a radioactive "tagging" material in accordance with the invention;

FIG. 3 is a side view of a rifle, illustrating the transmitted radiation pattern resulting from firing the cartridge of FIG. 1;

FIG. 4 is an enlarged vertical cross-section through the end of the rifle barrel, illustrating the formation of X radiation;

FIG. 5 is a cross-sectional view of the major elements of a beta-excited X-ray source;

FIG. 6 is a graph illustrating the energy distribution of X radiation for different exciting energies;

FIG. 7 is a graph showing the energy spectrum of a beta emitter;

FIG. 8 is a graph showing two energy spectra of beta-excited X-ray sources;

FIG. 9 is a graph showing different X-ray energy spectra plotted against target materials of different atomic numbers;

FIG. 10 is a graph showing X-ray energy spectra subdivided into successive energy regions;

FIG. 11 is a graph illustrating the time distribution of pulse amplitudes obtained from an X-ray detector;

FIG. 12 is a cross-sectional view of one embodiment of an X-ray transmitting device in a "nonbroadcasting" condition;

FIG. 13 is a cross-sectional view showing the X-ray transmitter of FIG. 12 in a "broadcasting" condition;

FIG. 14 shows another configuration of an X-ray transmitter; and

FIG. 15 illustrates the tracking system and its associated electronics for detecting, locating, and identifying unknown sources.

Prior nucleonics ranging systems

In recent years, a number of military and space applications have been found for nucleonics ranging and tracking systems. Nucleonics systems are systems in which a self-powered source of radiant energy and one or more detectors of said energy are utilized to measure a variable, such as distance, angle, density, or position. For example, such systems have been investigated and developed for tracking a missile during the lift-off phase of its trajectory. In these systems, a radioactive source is attached to the missile and the missile is tracked at two or more ground stations. The angular position and/or distance to the missile is determined. Nuclear tracking systems suitable for

at 65. The horizontal angle data is likewise fed to the same indicator from the aforementioned azimuth tracking system (not shown).

Sum signal $U+D$ is fed over lines 60 and 66 to a second amplifier 67. The output of amplifier 67 supplies range voltage information to lines 68 and 69. The range information on line 68 is fed to a conventional range indicating instrument 70. This range signal is also supplied over lines 68 and 71 to a bomb drop computer 72 and over line 69 to a pulse height analyzer 73 for purposes shortly to be described.

Pulse height analyzer 73 performs an amplitude discriminating measurement in well-known manner on the individual signal pulses from detectors 50. Their amplitudes or heights are proportional to the energies of the incident X-ray photons at the detectors, and the output of pulse height analyzer 73 contains information on the energy distribution spectrum of the received radiation. Specifically, a readout of information from the pulse height analyzer yields the number of counts found in successive energy regions for the incident radiation. There may thus be presented a simple readout of data summarizing the relative amounts of energies or pulse amplitudes, as previously discussed in connection with FIGS. 10 and 11.

The output from the pulse height analyzer is also fed to a known form of spectrum comparator 75 over line 74. Another input to the spectrum comparator 75, indicated only schematically in FIG. 15 by arrow 76, may supply simple spectrum signatures of known source characteristics.

The spectrum comparator 75 compares the energy spectrum from the pulse height analyzer 73 with a known spectrum from input 76 and transmits information over line 77 to a spectrum indicator 78. Indicator 78 may read out the identifying information on one of a plurality of neon lights, for example, to indicate visually which one of several energy spectra is most nearly matched by that of the sum signal $U+D$ from radiation detectors 50. Since the spectrum of energy from captured energy equipment can be predetermined, indicator 78 is analogous to an I.F.F. (identification-of-friend-or-foe) indicator such as is well known in radar tracking systems.

The spectrum identification information from comparator 75 is also supplied over lines 77 and 79 to bomb drop computer 72. Its function with respect to bomb drop computer 72 is to provide a "last instant" override signal as to whether or not a destroying bomb should be dropped by aircraft 7 (FIG. 1).

Bomb drop computer 72 receives elevation angle data over lines 64 and 80 and azimuth angle data from the other radiation tracking system (not shown) as indicated schematically by arrow 81. Also fed into the bomb drop computer 72 from other data sources (not shown) are the aircraft speed (arrow 82) and the aircraft altitude (arrow 83). The summation of information on aircraft speed and altitude, plus the measured information of distance and angular direction to the target, is used in well-known manner to provide an automatic bomb release command signal, indicated schematically by arrow 84, which is supplied to bomb-dropping mechanism in the aircraft. To increase the simplicity of the system and to reduce the total aircraft load, the functions of the bomb drop computer may, of course, be performed manually by the aircraft pilot.

In any event, details of the aircraft fire-control and indicator systems form no part of my present invention and have been illustrated schematically only for completeness of illustration. The tracking system shown in FIG. 15 is relatively simple as regards to number and complexity of components utilized. By using solid-state components and miniaturization techniques well known to the art, the aircraft tracking and control equipment may be made very lightweight, small, and reliable in operation. Although the invention has been particularly illustrated as applied to airborne detection, location, and identification of captured or "planted" equipment, it will be obvious that the invention may also be applied to land or sea operations. For example, two-dimensional tracking systems may be located in moving vehicles or on ships for use in surveillance or fire-control operations.

It will also be obvious to those skilled in the art that a series of beta-excited X-ray transmitters may be "planted" in or on the same or different pieces of military equipment. The spectral characteristics of the several X-ray transmitters may be made different by using different beta exciters for each source or by using target or shielding materials of different atomic numbers. By distinguishing between the different energy spectra received at the tracking equipment, the positions and time sequences of movement of different equipments can be determined. A further means of identifying different transmitters is to design them so that the protective low-Z shielding materials are removed or disintegrated after different time intervals.

The type of beta-excited X-ray transmitter exemplified by the rifle and cartridge of FIGS. 2–4 may also be applied to other devices and weapons where the initially dormant, beta-emitting material is brought into close physical proximity to the high-Z target material by explosive or mechanical means. The invention is equally applicable to heavier mortar or artillery weapons and to various forms of shells and munitions cartridges. The principal requirements are that the bore of the weapon be lined with high-Z material and that the radioactive charge be shielded by a low-Z material prior to firing.

While the invention has been illustrated with particular reference to nuclear detection and identification of captured enemy equipment, it may also be used in ordinary commerce as an aid in locating thefts or other misappropriations of valuable personal properties. For example, pretimed radiation capsules, as illustrated in FIGS. 12 and 13, may be concealed in briefcases, luggage or shipping containers for money, securities, art-works, jewelry, or other valuables, or concealed within the valuable property itself, so as to give a silent warning, after a predetermined time, to inspectors or other officials equipped with radiation monitors.

Thus, while certain specific embodiments of my invention have been shown and described, it will be understood that various other modifications may be made without departing from the principles of the invention. The appended claims are therefore intended to cover any such modifications within the true spirit and scope of the invention.

I claim:

1. A cartridge for firing in a gun to permit the location of the gun firing the cartridge, said cartridge comprising:
a cartridge case and bullet,
said cartridge case having an explosive firing charge,
the improvement comprising a radioactive material mixed in with said charge that leaves residual radioactive material in the gun after said cartridge is fired to produce radiation detectable at a remote location.

2. A cartridge as in claim 1, wherein said radioactive material is a beta-emitting isotope, said gun has a barrel of high Z material, and said detected radiation is beta-excited X-rays produced by said barrel acting as the target.

3. The cartridge, as described in claim 1, wherein the cartridge case comprises a shielding sleeve substantially between the radioactive material and said case to absorb substantially the radiation from said radioactive material.

4. The cartridge, as described in claim 1, wherein said radioactive material is a beta-emitting isotope, said gun has a barrel of high Z material, said detected radiation is beta-excited X-rays, produced by said barrel acting as the target, and said cartridge case comprises a shield sleeve substantially between said isotope and said case to absorb substantially the beta radiation from said isotope.

5. The combination, with a munitions cartridge or the

like of the type having a cylindrical casing containing an explosive charge, a projectile seated in one end of the casing and detonating means seated in the other end of the casing, of

a cylindrical liner composed of a material having a low atomic number interposed between said casing and said charge, and

a beta-emitting radioisotope dispersed throughout a major portion of said explosive charge.

6. The combination of claim 5 in which said explosive charge comprises smokeless powder pellets with said radioisotope embedded therein.

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United States Patent

[11] 3,557,366

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[73] Assignee Industrial Nucleonics Corporation
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[54] **ANGLE OF ATTACK INDICATOR USING A RADIOACTIVE SOURCE AND DETECTOR**
13 Claims, 1 Drawing Fig.

[52] U.S. Cl. 250/43.5, 250/83.3; 244/3.15
[51] Int. Cl. G01n 23/12
[50] Field of Search 250/43.5D, 106VC, 83.3; 244/3.15, 3.21; 102/70.2

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Primary Examiner—Archie R. Borchelt
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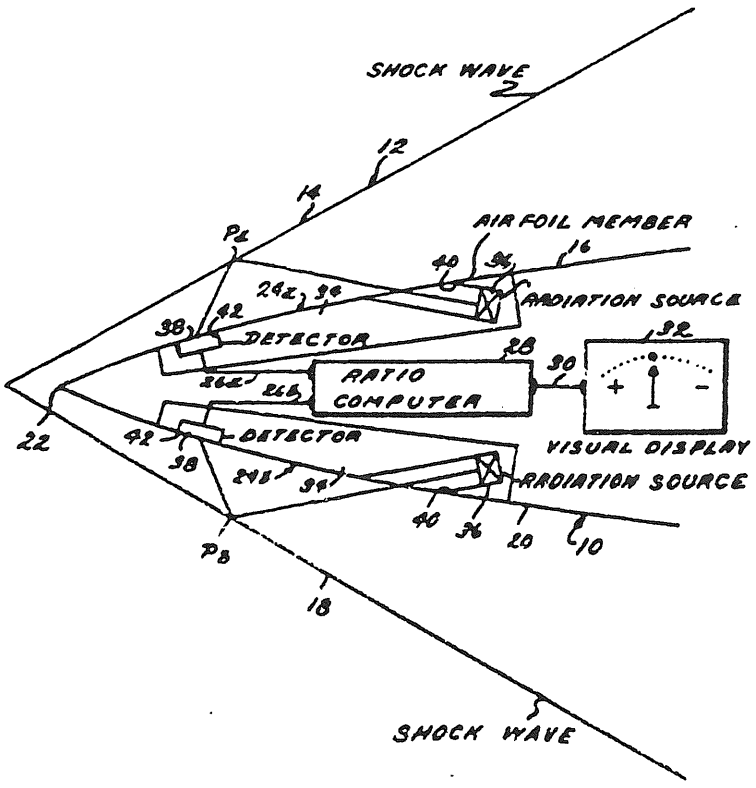
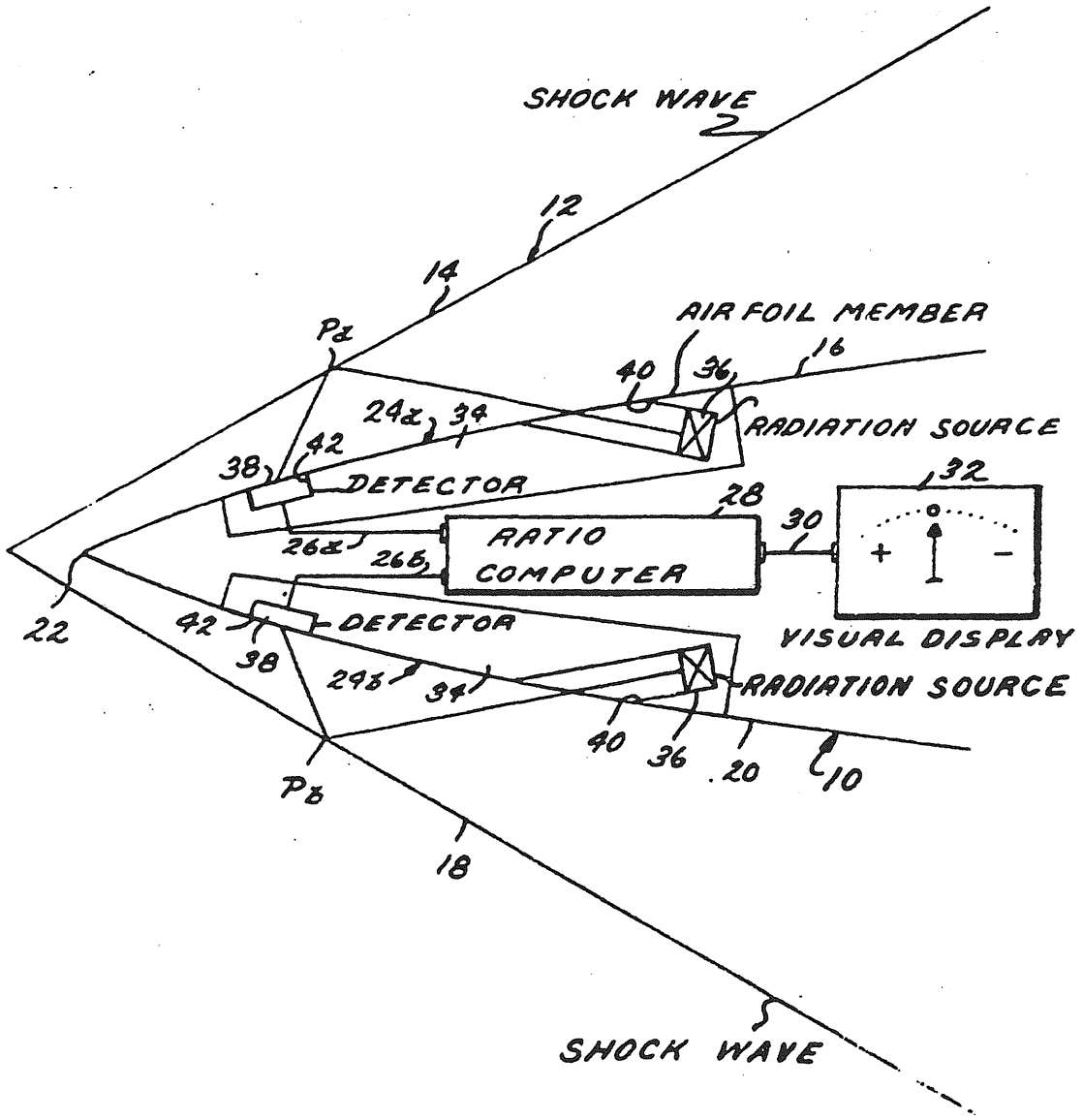
ABSTRACT: In order to provide an instantaneous indication of the angle of attack of a body traveling through the air at supersonic speeds, opposite surfaces of the leading edge of the body are provided with nucleonic radiation sources so directed as to intercept the shockwave created by the body with nucleonic radiation, some of which is reflected to radiation detectors also mounted on the body opposite surfaces. The outputs of the detectors are fed to a ratio computer and from there to a visual display device.





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ANGLE OF ATTACK INDICATOR USING A RADIOACTIVE SOURCE AND DETECTOR

BACKGROUND OF THE INVENTION

It is well known that as a body, such as a foil member, of an aircraft, space craft or the like travels through air at supersonic speed, a forwardly pointed, rearwardly divergent shockwave is normally setup about the body at the interface of subsonic and supersonic velocity air. For a given point on the upper and lower surface of the body, when the craft is in level flight, the distance between the respective point and the shockwave is a quantity which can be ascertained. When the craft veers, arches or dives, the shockwave moves with respect to the body upper and lower surfaces so as to become closer to one than it was during level flight.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a system for measuring the distance from diverse points on a body traveling through air at supersonic speed to the shockwave thereabout and providing an instantaneous, continuous visual result of comparing these distances so the operators of the craft may achieve a desired angle of attack. In the preferred embodiment, nucleonic radiations are beamed from the upper and lower sides of a foil member on the craft near the leading edge of the foil member and reflected from the shockwave to detectors mounted on the craft, the relative amounts of reflected radiation being directly proportional to a function of the relative proximity, so that a ratio of reflected radiation from the two sides of the shockwave provides a useful indication of angle of attack.

BRIEF DESCRIPTION OF THE DRAWING

In the drawing, the FIG. is a schematic view of a craft provided with an angle of attack indicator in accordance with the principles of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

The numeral 10 indicates the leading edge region of a portion of a flying craft proceeding leftwards, through the air at supersonic velocity so as to set up a shockwave 12 about the craft portion. The shockwave 12 has a segment 14 which passes over the upper surface 16 of the craft portion 10 and a segment 18 which passes under the lower surface 20 of the craft portion 10. It should be apparent that the craft portion 10 may be a foil member such as a wing, or a rotor blade or the like. It should also be apparent that the terms "upper" and "lower" are used herein in their usual sense, i.e. relating to a craft in right-side-up level flight, although the invention is by no means limited to use on a craft so oriented. Within the craft portion 10, near the leading edge 22, in the top of the portion 10 is provided at least one sensor 24*a* constructed and arranged to sense the distance between a point on the top of the craft portion 10 and a point on the shockwave segment 14. Similarly, the bottom of the craft portion 10 is provided near the leading edge 22 thereof with a sensor 24*b* constructed and arranged to provide an indication of the distance between a point on the craft bottom and the shockwave segment 18. Although only one sensor 24*a* and one sensor 24*b* is shown, in practice, several similar or identical sensors 24*a*, 24*b* may be employed.

Each sensor 24*a*, 24*b* conveys its information through a cable 26*a*, 26*b* to a ratio computer 28 of conventional design constructed and arranged to provide an output that is proportional to the ratio of the two input signals through 26*a*, 26*b*. The ratio computer output may be supplied via a cable 30 to an indicator panel 32.

Obviously, if the craft is one of the type to be controlled throughout flight by an onboard operator, the ratio computer 28 and visual display 32 are best located on the craft itself, whereas in instances where the craft is of the type to be at least optionally remotely controlled it is within the purview of this invention to locate the ratio computer 28 and/or the visual display 32 at the remotely controlled location and to provide means on the craft for transmitting output signals from the sensors 24*a*, 24*b* or ratio computer 28 to the remote control location.

Each sensor 24*a*, 24*b*, in the embodiment illustrated, includes a housing 34 within which is mounted a back scatter or reflection type nucleonic radiation device including a radiation source 36 and a detector 38. Each source 36 may provide any desired type of nucleonic radiation including electromagnetic radiation, for example, gamma rays from a pure gamma emitter, beta-excited bremsstrahlung X-rays or a controlled mixture of beta and bremsstrahlung X-rays as fully disclosed in the commonly assigned, copending U.S. Pat. application of Chope, Ser. No. 408,955, filed Nov. 4, 1964, now Pat. No. 3,439,166. As illustrated, the radiation from the respective sources 36 is directly outwardly and forwardly toward the segments 14, 18 of the shockwave at an acute angle and the respective detectors 38 are oriented at similar angles to receive radiation reflected or backscattered by the shockwave. The output signals from the detectors 38 which are conveyed from the ratio computer 28 and from there to the visual display meter 32, vary directly with the distance between the points P where the respective streams of radiation intercept the shockwave segments 14 and 18, and the respective detectors 38.

The housing 34 comprise radiation shields each having two collimated openings or windows 40 or 42 through which the radiation passes from and returns to the sensors 24*a*, 24*b*. The shields 34 prevent radiation from interfering with any other instrumentation on the craft.

As an example, if the sources 36 comprise a radioisotope that emits gamma photons, the photons travel in a straight line until they encounter the shockwave segments 14, 18, whereupon photons will be scattered in all directions. Some of these photons will be scattered or reflected back toward the respective detectors 38. Each detector 38 will then provide an electrical signal that is proportional to the number of photons received per unit time. Due to the placement of the shield 34, the only photons that reach the detector 38 of the sensor 24*a* are those which have been backscattered by the shockwave segment 14 at the point P_a and the only photons that reach the detector 38 of the sensor 24*b* are those which have been backscattered from the segment 18 of the shockwave at point P_b. Because the backscattered photons are diverging as they travel, the closer the point P_a, P_b is to its respective detector 38, the greater the number of photons which will reach the respective detector per unit time.

Each detector 38 may be any one of several types of conventional detectors: for example, a scintillator, an ion chamber, or a solid-state radiation detector.

The output of each detector 38 is an analogue signal that may be readily amplified if necessary, by conventional amplifying devices to furnish an acceptable signal for the ratio computer 28.

In the figure, the craft is shown proceeding toward the left in level flight, the points P_a and P_b being equidistance from the respective detectors 38. Thus the ratio computer computes a ratio of one which is supplied to the visual display device 32 via the cable 30 to provide a null indication. Upon diving or climbing, the resultant movement of the shockwave with respect to the craft portion 10 will be picked up by the respective detectors 38 as an increase in back scattered radiation detected by one and a decrease in backscattered radiation detected by the other. This information supplied to the ratio computer via the cables 26*a*, 26*b* will result in a proportionate deflection of the indicator of the visual display device in a positive or negative sense from the null position thereof, according to a preselected convention. Although the display device 32 as shown is of the type having a needle constructed and arranged to sweep over a calibrated dial, it would be within the purview of the invention to supply the output of the

ratio computer 28 to visual displays of other conventional type as will occur to those of ordinary skill in the art upon reading this disclosure.

Although in the preferred embodiment shown in the drawing, the two sensors 24*a*, 24*b* are on opposite surfaces of the foil member, the detector of each being forward of the radiation source thereof and the device which converts the data provided by the sensors into input for a meaningful visual display is a ratio computer, there are viable alternatives to each of these features, within the purview of the invention. The two sensors will also operate to provide the desired data, when mounted one behind the other on a single surface, for instance the upper surface, of the foil member. Then if the distance between one sensor and its sensing point at the shockwave is, for instance X, when the craft is in level flight, and the distance between the other sensor and its sensing point at the shockwave is, for instance 3X, a change of angle of attack produces a movement of the shockwave relative to both sensors so that the two distances are for instance X-*a* and 3X-*b*.

It should now be apparent that such changes, once accurately and rapidly sensed in accordance with the present invention, are susceptible of being compared with one another and/or with previously obtained standards in order to provide a visual display susceptible of rapid, meaningful interpretation. Instead of a ratio computer, the manipulation of the sensor-provided data can be successfully accomplished using a conventional comparator provided with an analogue or template of the location of the shockwave at the respective sensing points as a function of most significant parameters, including air density and velocity of the foil with respect to the air. These analogues or templates vary in shape, depending principally upon the shape of the foil member and resistance it presents to the flow of air over its exterior surface and are empirically constructed using established aerodynamic principles and techniques during wind tunnel tests on models of the foil members and during flight tests of prototype craft. In instances where sensor-provided data is compared with previously obtained values to provide an indication of angle of attack, by measurement of variation from the previously obtained values, the number of sensors supplying input to the comparator(s) may vary upwards from one.

The sensors 24*a*, 24*b*, will also perform satisfactorily when the respective radiation sources are mounted where the respective detectors are shown and vice versa or closer or further from one another so long as the respective radiation sources are so directed as to emit radiation which will encounter the shockwave and the respective detectors are so directed as to be in the path of radiation emanating from the respective radiation source that is reflected or backscattered from the shockwave. Beside operations directly upon the data provided by the sensors 24*a*, 24*b*, conventional integrators may be interposed in the circuits 26*a*, 26*b* for instance to integrate the sensor-to-shockwave distance measurements against time or velocity of the foil with respect to the air. The resultant signal may then be fed to a ratio computer 28, comparator or other device for constructing angle of attack intelligence from the sensed information, and from there to a visual display 32. Of course, as needed, other conventional components such as amplifiers, filters, gates and radiation shielding may be incorporated in the circuits 26*a*, 26*b*.

For some purposes, a comparison or ratio computation of the output signals provided by the detectors 38 may not be necessary, the output signals being then provided directly to the visual display device 32 which in that instance may exhibit visual indications of the magnitude of each signal separately in a side-by-side relationship, for instance on two bar graph displays.

It should now be apparent that the angle of attack indicator as described hereinabove, possesses each of the attributes set forth in the specification under the heading "Summary of the Invention" hereinbefore. Because the angle of attack indicator of the invention can be modified to some extent without departing from the principles of the invention as they have been outlined and explained in this specification as will become apparent to those of ordinary skill in the art upon reading this disclosure, the present invention should be understood as encompassing all such modifications as are within the spirit and scope of the following claims.

I claim:

1. An angle of attack indicator for a craft of the type that is constructed and arranged to pass through the air at supersonic velocity, setting-up a shockwave thereabout comprising: first nucleonic radiation sensor and source means mountable on the craft at a first location thereon and constructed and arranged to provide an output signal proportional to the proximity of a first point on the shockwave to the sensor means; second nucleonic radiation sensor and source means mountable on the craft at a second location thereon and constructed and arranged to provide an output signal proportional to the proximity of a second point on the shockwave to the second sensor means; and means for transmitting the output signals of the first and second sensor means to a ratio computer for providing an indication of the angle of attack of said craft.

2. The indicator of claim 1 further comprising a ratio computer located on board said craft; and wherein said transmitting means comprises a cable connecting said ratio computer to said first and second sensor means.

3. The indicator of claim 2 further comprising a visual display device on board said craft, said visual display device being operatively connected to said ratio computer and being constructed and arranged to receive the output thereof and provide a changeable visual display proportional thereto.

4. The indicator of claim 1 wherein each sensor and source means includes a radiation source constructed and arranged to emit nucleonic radiations toward a preselected region on the shockwave, and a detector constructed and arranged to receive radiations emitted from the respective radiation source then back scattered or reflected from said shockwave.

5. The indicator of claim 4 wherein each sensor and source means further includes a housing of radiation shielding material and having means defining a first collimating recess therein in which the respective radiation source is received and a second collimating recess therein in which the respective detector is received.

6. The indicator of claim 5 wherein the first and second recesses of each sensor and source means are angled with respect to one another so as to have a longitudinal axis intersection spaced outwardly from the craft.

7. The indicator of claim 4 wherein the first sensor and source means is mounted in the upper side of a foil member of the craft near the leading edge of the foil member and adapted to sense proximity to a segment of the shockwave that passes over the foil; and wherein the second sensor and source means is mounted in the lower side of the foil member of the craft near the leading edge of the foil member and adapted to sense proximity to a segment of the shockwave that passes under the foil.

8. An angle of attack indicator for a craft of the type that is constructed and arranged to pass through the air at supersonic velocity, setting up a shockwave thereabout, comprising at least one sensor mounted on the craft proximate the shockwave, including a nucleonic radiation source emitting radiation encountering the shockwave, and a detector so directed toward the shockwave as to receive nucleonic radiation emitted by the nucleonic radiation source then reflected or backscattered by the shockwave, said detector including output means providing a signal proportional to said nucleonic radiation received by said detector.

9. The angle of attack indicator of claim 8, further including a visual display device calibrated in angle of attack units; and comparison means connected to said detector output means and providing input to said visual display device, said comparison means being constructed and arranged to convert said detector output means signal to an input signal for providing angle of attack visual indications on said visual display device.

10. A method for indicating the angle of attack of a craft of the type that is constructed and arranged to pass through the air at supersonic velocity, setting up a shockwave about the craft, comprising: emitting nucleonic radiation from the craft toward a selected region on the shockwave, detecting from the craft nucleonic radiation reflected or backscattered from the selected region and providing a signal proportional to the detected nucleonic radiation.

11. The method of claim 10 further including contemporaneously: emitting nucleonic radiation from the craft toward a second selected region on the shockwave, detecting from the craft nucleonic radiation reflected or backscattered from the second selected region and providing a signal proportional to the detected nucleonic radiation.

12. The method of claim 11 further including comparing the two signals with one another to provide a ratio thereof proportional to the angle of attack of the craft.

13. The method of claim 11 further including: providing an analogue of the position of the shockwave with respect to the craft at various angles of attack and comparing at least one of the signals to the analogue to provide an indication proportional to the angle of attack of the craft.

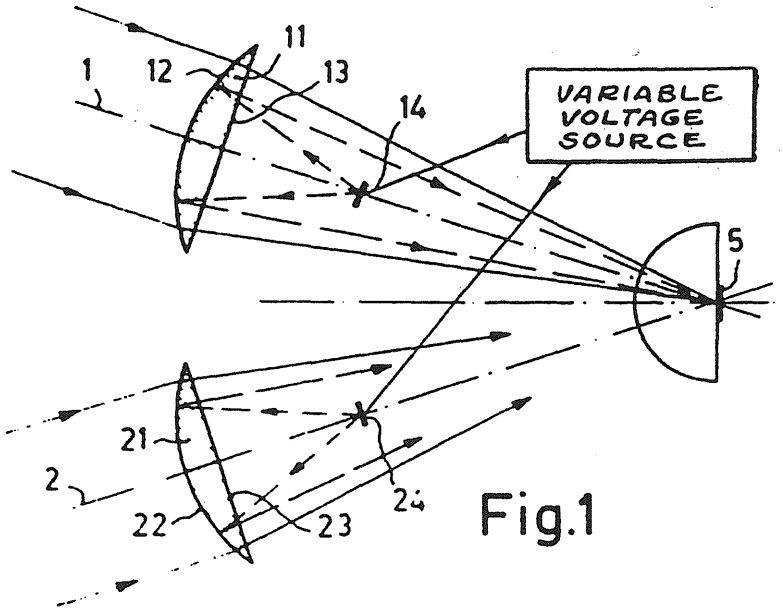

Fig.1

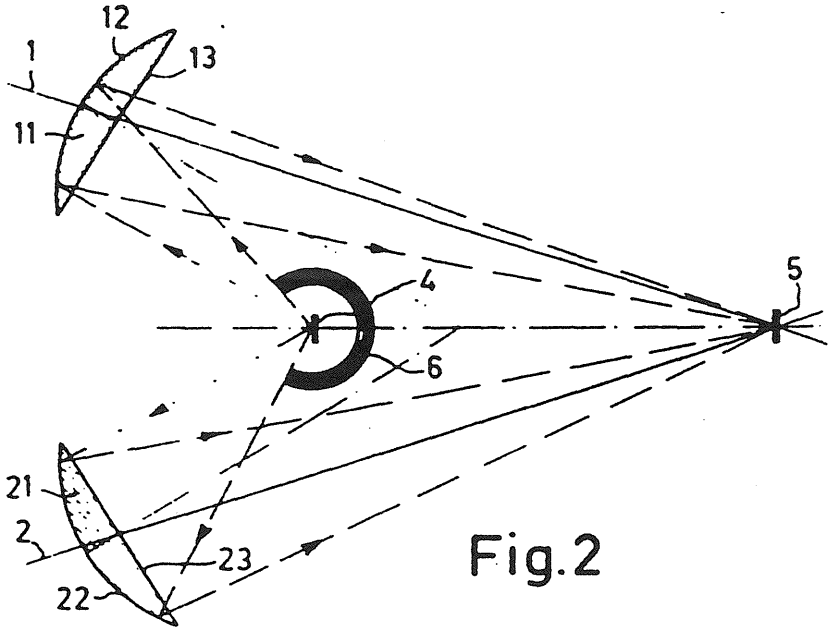

Fig.2

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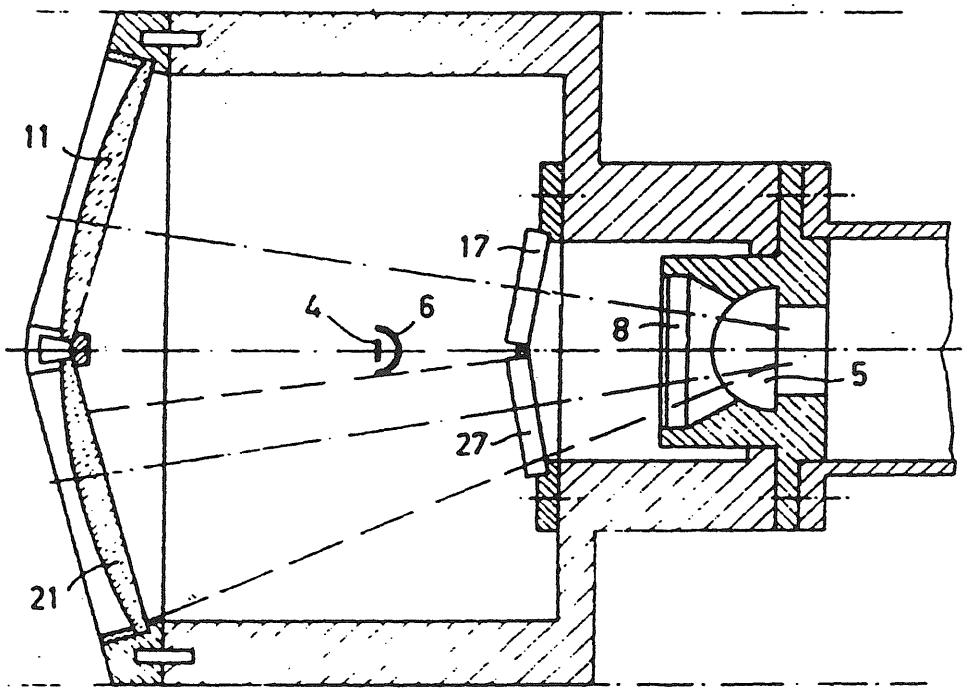

Fig.3

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LIGHTING DEVICE COMPRISING TWO OPTICAL SYSTEMS AND A RADIATION SENSITIVE DETECTOR

The invention relates to a sighting device equipped with two optical systems which each consist of an optical modulator and a lens. The optical axes of the two optical systems intersect at and with a radiation-sensitive detector. Such a device may form part of a horizon sensor which is used to control and maintain the attitude of a space vehicle.

In the last 10 years the problem of controlling and maintaining the attitude of a space vehicle has been extensively studied and many solutions have been proposed, none of which, however, is entirely satisfactory.

Of the three movements performed by any passive free-body moving in space the rolling and the pitching can be controlled by a device including a horizon sensor. The third movement, the yawing, can only be corrected by means of an astronomic reference point (for example a star).

The horizon sensor is designed so that when a heavenly body or planet is sighted an image thereof is formed by means of an optical system on at least one detector sensitive to thermal or photoelectric radiation.

When the attitude of the space vehicle is correct, all the detectors receive exactly equal radiation intensities (which may be zero). At the slightest deviation the detectors receive different radiation intensities. The signals from the detectors are applied through a comparatively bulky electronic circuit to devices which cause the vehicle to assume the desired attitude by means of gas jets. In this process the rotation of a flywheel or any other device capable of changing the position of one of the axes of the vehicle may be used. For a satellite circling the earth the latter planet will be used as a reference point. Owing to the atmosphere and the variations in luminous intensity of the light from the surface of the earth, however, it is impossible to use the visible radiation and hence only the sufficiently constant infrared radiation can be utilized by the detection device.

Two types of detectors may be used:

1. Photoelectric detectors, in which each photon individually and entirely transfers its energy to an electron of the radiation-sensitive material. These detectors are rarely used, because their sensitivity is low and their detection threshold (the value of the wavelength above which no radiation is detected) is too high. In addition, if these detectors are to be used in the middle infrared range, they must be cooled to a low temperature.

2. Thermal detectors, in which the energy of the radiation received is converted into heat. Owing to their sensitivity, which is independent of the wavelength, they are to be preferred in the form of bolometers or thermopiles to the first-mentioned detectors. Bolometers have the advantage of fast response. Their greatest disadvantage is, however, that they show a certain thermal drift. In operation they require the application of a direct voltage, by which they are heated. This results in a drift which may become considerable and is superposed on the signal produced by the incident radiation. Consequently, weak radiation cannot be measured. The influence of this drift on the measurements has been eliminated by distinguishing between the signals produced by the incident radiation and the signals produced by the heating due to the application of the direct voltage; to this end the incident radiation is modulated. Thus, the modulated component of the output signal of the bolometer corresponds only to the signal produced by the incident radiation.

Two types of modulators are used: opticomechanical and electro-optical. When a high reliability is required, which is the case in long-life satellites, the use of mechanical systems is avoided as far as possible. Hence there is an increasing interest in electro-optical modulators based on the property of light absorption exhibited by the free electrons in a solid. These modulators basically consist of PN junctions of semiconductors to which alternating voltages are applied.

A horizon sensor comprises two sighting devices, one for the North-South direction and one for the East-West direction. Each sighting device includes two optical systems the axes of which meet at a given angle in the axis of a bolometer. The direction of the bisector of this angle relative to a fixed direction in space provides an indication of the orientation of the vehicle. The sighting device is proportioned so that when the direction of the bisector coincides with the direction of sighting the output signal of the bolometer is zero.

The two optical systems of a sighting device each comprise a lens and a modulator. The beams emerging from the optical systems converge on the same bolometer. The two modulators operate at the same frequency but with opposite phase. A deviation from the sighting direction, which shows itself as a displacement of the image of a planet or a star, supplies to the bolometer signals having the same frequency but different strengths and phases. The strength of the difference signal provides information about the magnitude of the deviation, and the phase of the difference signal provides information about the direction of the deviation.

As has been mentioned hereinbefore, it is the purpose of the modulation of the radiation to eliminate errors due to the thermal drift of the bolometer. However, there still remain errors due to optical asymmetries which arise from geometric factors but also from factors inherent in the materials used.

The semiconductor materials used in the manufacture of the lenses and modulators (for example, germanium for radiations having wavelengths in the middle of the infrared range) may have transmission coefficients which are slightly different from element to element, which results in the radiation being asymmetrically transmitted with consequent shifting of the zero point. A correction of the zero displacement may be effected in the electronic circuit associated with the detector, but for fundamental reasons this correction is preferably effected at the level at which the error is produced, i.e., in the infrared detection.

It is an object of the present invention to eliminate the errors due to asymmetrical transmission. For this purpose it is characterized in that there is inserted between the lenses of the optical systems and the radiation-sensitive detector at least one auxiliary radiation source, the lenses of the optical system forming catadioptric systems for imaging the auxiliary radiation source on the radiation-sensitive detector. The output signal of the radiation-sensitive detector due to the auxiliary radiation is equal to the interference signal caused by the apparent asymmetry. However, the two signals have opposite signs. The fact that the lenses of the optical systems can be used not only for their proper tasks but also for imaging the auxiliary radiation source provides a large advantage. The radiation energy of the auxiliary radiation source required to supply a given compensating illumination for the detector may be considerably smaller than in the known systems, with a consequent considerable decrease of the power consumption. Further, the aperture angle of the compensating beam coincides with the angle in which the interfering radiation is operative and approximates to that of the optical system itself, permitting a highly satisfactory compensation which is independent of local variations of the optical properties of the detector system.

The invention will now be described more fully with reference to the accompanying drawings, in which

FIGS. 1, 2 and 3 show, by way of example, embodiments of a device according to the invention.

FIG. 1 shows a sighting device including two optical radiation paths 1 and 2. In each radiation path there is inserted an objective 11 or 21 respectively which is made of germanium and transmits infrared radiation. The transmissivity of surfaces 12 and 22 of these lenses is not a maximum and hence these surfaces may serve as mirrors for compensation elements 14 and 24 respectively. Since the refractive index of germanium is about 4, the reflection coefficient of a not specially treated surface is comparatively high, i.e., about 36 percent. Together with the other elements of the optical system, especially the objective itself, this untreated surface constitutes a catadioptric system which forms a suitably magnified image of the compensation source on the radiation-sensitive element 5.

The compensation sources 14 and 24 each comprise a small metal surface through which a weak electric current flows, which gives rise to heating and hence to the emission of radiation.

In the embodiment shown in FIG. 1 such a heat source is inserted in each radiation path so as to be located in the optical axis of the respective sighting device. Each heat source is fed with an adjustable electric voltage in a manner such that a slight difference between the voltages supplied to the two sources, i.e., a temperature difference between them, can be used to compensate for asymmetry errors.

FIG. 1 shows the ray paths which corresponds to the two functions of each lens: the imaging of an object at infinity is shown in full lines and the imaging of the compensation source is shown in broken lines.

FIG. 2 shows a second embodiment of a device according to the invention. In this device a single source 4 is used to equalize the radiations following both paths 1 and 2 in the zero condition. To enable the rays which image the single source 4 on the radiation-sensitive detector 5 to be equally divided between the two paths, the optical centers of the two paths must coincide and lie on the line joining the source 4 to the detector 5. This is obtainable by tilting both objectives 11 and 21 in the manner shown in FIG. 2. In this case the electric supply has a fixed value. The effective luminous flux radiated along each path now is determined by a screen 6 by the displacement or rotation of which the effective luminous flux following each of the paths can be regulated.

FIG. 3 shows a practical embodiment of a horizon sensor using two optical systems. The two lenses are again designated 11 and 21, reference numeral 5 designates a bolometer and reference numerals 17 and 27 designate infrared modulators. A filter 8 enables a band having a selected value to be transmitted. The modulators 17 and 27 are fed in phase opposition, the intensity and the phase of the infrared signal received by the bolometer 5 indicating the value and the sign respectively of the deviation.

The bolometric element is disposed in the image focus of the lenses 11 and 21 and the image nodal points of these lenses are located so that the two images of the bolometer at infinity closely approach the horizon.

A horizon sensor comprises at least two sighting devices of the above-mentioned kind, one of these sighting devices indicating the deviation in the North-South direction and the other that in the East-West direction.

What is claimed is:

1. A device for sighting on a remote source of radiation, comprising a first lens, a modulator aligned with the first lens along an optic axis, a second lens, a second optical modulator aligned with the second lens along a second optical axis intersecting the first optical axis, a radiation-sensitive detector in the path of both optic axes, whereby the radiation from the remote source is imaged on the radiation-sensitive detector, and a local source of radiation between the lenses and the radiation detector for projecting radiation in the direction of the lenses, at least one internal surface of each lens having sufficient reflectivity to comprise a catadioptric system for imaging the auxiliary radiation source on the radiation-sensitive detector.

2. A device as claimed in claim 1, wherein an auxiliary radiation source is disposed in each optical axis passing through the optical center of a lens and the center of the radiation-sensitive detector.

3. A device as claimed in claim 2, wherein the radiation can be separately regulated for each source.

4. A device as claimed in claim 1, wherein one auxiliary radiation source is provided and that the point of intersection of the axes of the optical systems lies on a line which joins the auxiliary radiation source and the radiation-sensitive detector.

5. A device as claimed in claim 4, wherein the auxiliary radiation source is surrounded by an apertured screen for limiting the auxiliary radiation to the lenses.

6. A device as claimed in claim 5, wherein the screen is movable.

7. A device as claimed in claim 1, wherein the radiation source comprises a small metallic surface through which an electric current flows, the radiation emitted by the or each surface being directed to the lenses.

8. A device as claimed in claim 1, wherein the surfaces of the lenses turned to the auxiliary radiation sources are coated with antireflection layers.

9. A device as claimed in claim 8, wherein the lenses are made of a material having a high refractive index.

* * * * *

United States Patent

Duffey et al.

[15] **3,638,020**

[45] **Jan. 25, 1972**

[54] MINERAL-DETECTION APPARATUS

[72] Inventors: **Dick Duffey, Adelphi; Peter F. Wiggins, Annapolis; Frank E. Senftle, Chevy Chase, all of Md.**

[73] Assignee: **The United States of America as represented by the United States Atomic Energy Commission**

[22] Filed: **May 26, 1970**

[21] Appl. No.: **40,644**

[52] U.S. Cl. ..... 250/83.3 R, 250/106 S

[51] Int. Cl. G01t 4/6

[58] Field of Search ..... 250/83.1, 83.3 R, 83.6 W, 106 S, 250/84.5

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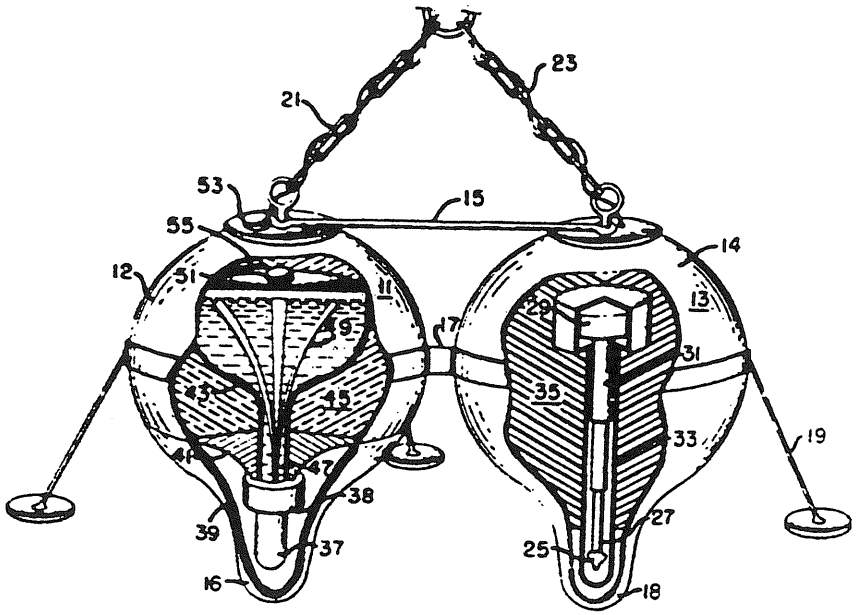
Primary Examiner—James W. Lawrence
Assistant Examiner—Davis L. Willis
Attorney—Roland A. Anderson

[57] **ABSTRACT**

A marine mineral-detection apparatus is described including a ^{252}Cf source of neutrons and a lithium-drifted germanium radiation detector shielded from the neutron source. The neutron source is mounted on an extensible member supported within a mass of neutron-shielding material. The source is extended outside the neutron shield to bombard surrounding mineral values with neutrons. Elements capturing neutrons give off prompt gamma radiation with discrete energies. The radiation detector resolves the radiation into distinct energy peaks for identifying the elements present in the mineral values.

4 Claims, 2 Drawing Figures



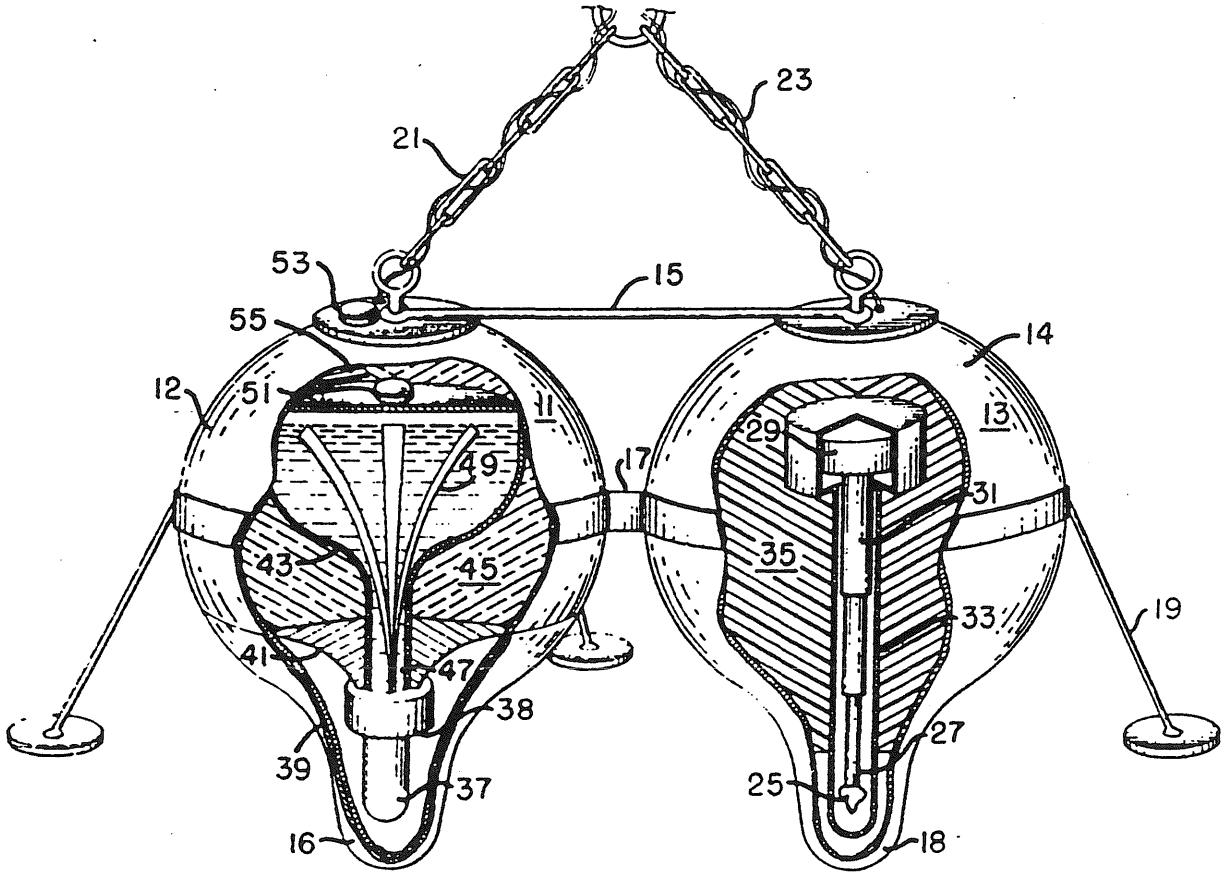


Fig - 1

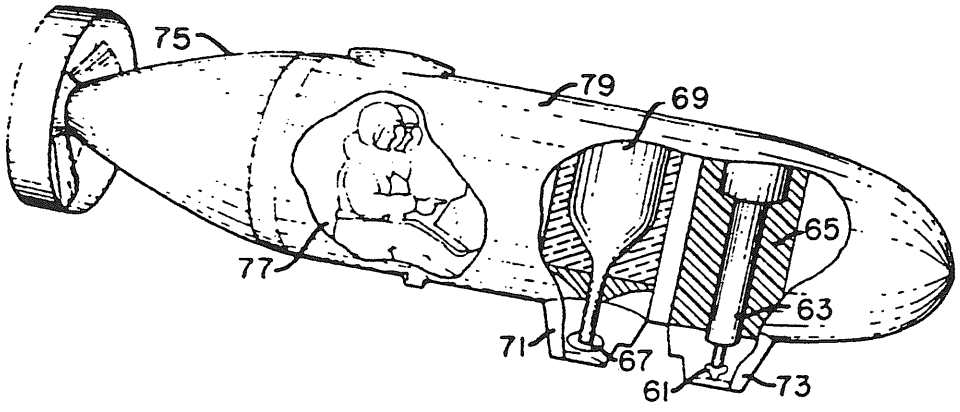


Fig - 2

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MINERAL-DETECTION APPARATUS

BACKGROUND OF INVENTION

The present invention was made in the course of, or under, a contract with the United States Atomic Energy Commission.

FIELD OF THE INVENTION

The present invention relates to mineral exploration devices employing neutron activation analysis. This invention is particularly applicable to in situ exploration of the ocean floor where it is expected that mineral values are disseminated as relatively low-grade stratiform deposits. It may also have value in the general field of geochemical mapping.

Neutron activation analysis can be used in a variety of ways to identify unknown elements. One widely employed method is to convert the unknown element into a short-lived radioisotope and monitor the radiation resulting from radioactive decay. Gamma radiation originating in this manner will hereinafter be called activation or delayed gammas. Delayed gammas seldom have energy levels in excess of 1.5 mev. Thus the useful activated volume at the ocean floor is limited and widely disseminated or randomly scattered minerals may not be effectively detected from delayed gamma radiation. The presence of background radiation from natural emitters such as ^{40}K and the thorium-uranium series further complicate delayed gamma radiation measurements. More significantly the abundant sodium and chlorine in ocean waters are easily activated by neutron radiation and the decay of their activation products tend to mask radiation from less concentrated minerals.

Another form of analysis with neutrons relies on prompt gamma detection for identification of neutron bombarded elements. When an element captures neutrons a burst of capture gamma radiation is produced after about 10^{-14} to about 10^{-8} seconds but prior to radiation from any radioisotope decay. Generally, the slower neutrons are more likely to be captured by a given element. Spectra signatures including a plurality of capture gamma peaks with distinct energies can be determined for various elements and employed to identify these elements during mineral exploration. However, a gamma radiation detector with energy discrimination to a few hundredth of an mev. must be employed to obtain useful capture gamma signatures. Capture gammas are at energy levels as high as 9 mev. and therefore will reveal the minerals within a larger size sample than will delayed gammas which normally do not exceed about 1.5 mev.

Use of fast neutrons for mineral detection will produce gamma radiation from inelastic scattering reactions as will as capture gammas. Both of these types of radiation occur and diminish prior to delayed gammas and accordingly are generally termed prompt gammas. Inelastic scattering gammas may have some value in mineral identification but can blur or confuse capture gamma signatures. Consequently it is desirable to minimize the quantity of fast neutrons emitted from a neutron source employed for capture gamma spectroscopy.

DESCRIPTION OF PRIOR ART

Marine mineral exploration is presently accomplished by physically removing samples from on or beneath the ocean floor. One manner of obtaining samples is through use of hollow drill sections and recovery of the drill cores. Since many ocean minerals are believed to be in low concentration disseminated deposits, a large number of drill core samples at different locations may be required to determine if a mineral field warrants mining and recovery costs. Consequently, such sampling methods are time consuming and expensive.

In general, neutron activation analysis to date has been based on the detection of delayed gamma radiation in terrestrial mineral exploration. For example, see "Californium-25, Proceedings of a Symposium," pp. 321–346, sponsored by the New York metropolitan Section of the American Nuclear Society, Oct. 22, 1968, J. J. Barker, Ed. USAEC CONF-681032, Jan. 1969. Application of delayed gamma radiation techniques to marine mineral exploration would be subject to the foregoing disadvantages and difficulties.

SUMMARY OF INVENTION

Therefore, it is an object of the present invention to provide an in situ mineral detection apparatus.

It is also an object to provide a mineral detection apparatus which can examine a large volume sample in search of widely disseminated mineral values.

It is a further object to provide a marine mineral detection apparatus for locating deposits in the presence of background radiation and radiation from activated isotopes of sodium and chlorine.

In accordance with the present invention there is provided a ^{252}Cf source of neutrons mounted on an extensible member within a body of neutron-shielding material. The ^{252}Cf can be extended outside the shielding material to irradiate surrounding mineral values with neutrons. A lithium-drifted germanium crystal for radiation detection is spaced and shielded from the ^{252}Cf source. The crystal senses prompt gamma radiation produced by the irradiated mineral values with sufficient discrimination of energy peaks to define energy spectra signatures for element identification. The crystal is contacted and cooled by multiple heat-conduction bars submerged at one end opposite the crystal in a liquid refrigerant.

DESCRIPTION OF THE DRAWINGS

The present invention is illustrated in the drawings wherein:

FIG. 1 is a partially cutaway perspective view of a mineral detection apparatus;

FIG. 2 is a partially cutaway perspective view of a submersible vehicle for lowering the mineral detection apparatus to the ocean floor.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now to FIG. 1, a gamma ray detection unit 11 and a neutron source unit 13 are shown rigidly connected together by a suitable rod 15 and interlocked bands 17. Units 11 and 13 are enclosed in generally spherically shaped housing 12 and 14, respectively. Both housings 12 and 14 have projection of reduced diameter 16 and 18, respectively, pointed downwardly for penetrating surface sediment. A plurality of legs 19 are attached to bands 17 to support the units 11 and 13 on the surface where they are to be used. Chains 21 are suitably attached to lower the units to the ocean floor and to provide a retainer for power cables 23 entering each unit.

The neutron source unit 13 includes an encapsulated Californium–252 neutron source 25. The ^{252}Cf undergoes spontaneous fission to produce a higher sustained neutron yield for a given source size than other known neutron sources. ^{252}Cf has an average neutron energy of 2.3 mev. such that with little moderation the quantity of inelastic scattering gammas produced by this neutron source are minimized and capture gamma signatures can be clearly obtained. It is therefore particularly well suited for use in a mobile mineral detection unit for seeking widely disseminated marine minerals. About 50 to 250 micrograms of ^{252}Cf is sufficient for the present application but larger or smaller amounts may be used to vary the neutron flux.

The ^{252}Cf is encapsulated in an impervious metal material to prevent loss of the valuable isotope. Suitable encapsulating materials include zirconium, niobium, and tantalum. These metals have insignificant capture gamma spectra and are chemically and physically compatible with ^{252}Cf. Zirconium has only one relatively important capture gamma peak at 6.29 mev. while niobium has two peaks which are not very prominent and tantalum has no capture gamma peaks of importance. Nevertheless, niobium and tantalum absorb more neutrons and consequently their overall gamma ray emission is higher than that of zirconium. Therefore in regard to source background radiation, zirconium and zirconium alloys are the

preferred encapsulating materials of the three metals mentioned as suitable.

The encapsulated ^{252}Cf neutron source 25 is shown supported by an extensible member 27 in its extended position for irradiating surrounding mineral values in geologic strata. One manner os extending and retracting member 27 is to provide a reversible and rotary servomotor 29 driving a helically coupled telescoping shaft 31. Member 27 can be prevented from rotating with shaft 31 by a sliding pin and groove connection (not shown) between member 27 and a nearby stationary wall.

The ^{252}Cf neutron source 25, extensible member 27, and the servomotor 29 are enclosed within an internal pressure vessel 33. Housing 14 may thereby be maintained at ambient pressure and thick exterior walls are unnecessary. Pressure vessel 33 and the walls of housing 14, especially the lower portions thereof, can be constructed of the recommended encapsulating materials or of a plastic such as fiberglass to limit capture gamma emissions from the construction materials. A hydrogenous neutron-shielding material 35, such as polyethylene, is provided in the remaining upper portion of housing 14 leaving the lower portion of projection 18 substantially free of neutron-shielding material. A thin layer of hydrogenous or other neutron-moderating material (not shown) can be placed on the inside walls of projection 18 to reduce the energy of neutron radiation if the surrounding water will not be an adequate moderator.

When storing or transferring the unit, the ^{252}Cf is retracted into the upper central portion of vessel 33 and is substantially surrounded by a uniform thickness of shielding material 35 to limit radiation emission. When the unit is in position with projection 18 penetrating surface sediment, such as may be found on the ocean floor, the ^{252}Cf is extended into the lower portion of projection 18 below shielding material 35 as shown. Surrounding geologic strata will thereby be irradiated with neutrons to produce capture gamma emissions from mineral values contained therein.

The gamma ray detection unit 11 includes a lithium-drifted germanium crystal 37 disposed in the hollow projection 16 of housing 12. Other radiation detectors having gamma energy resolution substantially equal to that of the Ge(Li) crystal might also be used, e.g., having gamma energy resolution to about 10 kev. for peaks in the mev. range. Crystal 37 is encapsulated in a cadmium and lithium shield to prevent damage resulting from neutron radiation. A preamplifier 38 sufficiently increases the electrical signal from crystal 37 for transmission to a recording pulse height analyzer and spectrometer (not shown) in a support vessel or vehicle.

A protective layer or coating of neutron-absorbing material 39 such as an aluminum-boron alloy is applied on the outside of housing 12. This protective layer prevents gamma interference resulting from neutron capture by the wall materials of housing 12. A layer of gamma shielding material 41, such as lead, is placed above the Ge(Li) crystal 37 to block background and capture gamma radiation originating above the unit.

A reservoir 43 of liquid nitrogen or other suitable refrigerant is disposed in the main body portion of housing 12. The refrigerant reservoir is spaced from the housing 12 wall to provide a peripheral chamber containing thermal insulation 45. Metal wires or fingers 49 extend in a passageway 47 from the Ge(Li) crystal 37 through the preamplifier 38 into refrigerant reservoir 43. The fingers transfer excess heat from the crystal 37 into the liquid refrigerant. The refrigerant is maintained at a constant boiling temperature by a pressure relief valve 51 in the wall of reservoir 43. The pressure inside housing 12 is maintained slightly above the outside pressure by a second pressure relief valve 53. Thus as the unit is lowered into the ocean the heat produced by the Ge(Li) crystal 37 provides pressurization in the peripheral chamber containing insulation 45 to prevent collapse of housing 12. Supplemental heaters and remote pressure-monitoring devices (not shown) may be provided to ensure sufficient pressure in housing 12.

An attitude indicator 55 is placed within housing 12 to transmit electrical signals indicating the orientation of the unit. The unit may thereby be positioned with the projections of reduced diameter 16 and 18 always pointed downwardly into the ocean bottom.

In one manner of operating the apparatus of the present invention for marine mineral exploration, the detector and associated electronics are calibrated on board the support vessel with capture gamma rays from pure materials. The unit is then further calibrated by lowering it into the water to identify prompt gamma ray peaks emitted by sodium and chlorine. Signals from the attitude indicator are then used to position the unit upright on the ocean floor with the projections of reduced diameter 16 and 18 penetrating the surface sediment. With the ^{252}Cf source 25 extended, the signals from the Ge(Li) crystal are counted and recorded. The sea water spectrum can then be subtracted from that obtained at the ocean floor by raising the unit several feet about the surface and taking a second reading. The net spectral signatures thus read from the detector unit can be compared with known spectral signatures for suspected elements and the minerals in a particular location at the ocean bottom identified. Capture gamma signatures for several elements such as gold and manganese are given in the following publication by the inventors of the present mineral-detection apparatus: "Mineral Exploration of the Ocean Floor by In Situ Neutron Absorption Using A Californium–252 Source," Marine Technology Society Journal, Vol. 3, No. 5, pp. 9–16, Sept.–Oct. 1969. As explained in this publication, a spectral signature may comprise several capture gamma peaks at distinct energy levels. Interference from another element will probably only obscure one of the peaks making up the signature and the element is identifiable notwithstanding the interference. For instance, manganese emits capture gamma radiation with peaks at 6.04, 6.24, 6.55 and 6.65 mev. Chlorine has an interfering capture gamma peak at 6.64 mev., but manganese can still be identified from its remaining capture gamma peaks.

Another embodiment of the present invention is shown in FIG. 2. A submersible vehicle is shown having a pair of hollow projection 71 and 73 extending from its bottom portion. A ^{252}Cf source of neutrons 61 is mounted on an extensible member 63 for extending into and retracting from projection 73. Neutron-shielding material 65 surrounds the retracted position of the neutron source 61. A Ge(Li) radiation detector 67 is disposed within projection 71 for sensing prompt gamma radiation produced by neutron absorption into surrounding mineral values. A reservoir 69 of a liquid nitrogen provides refrigeration for cooling the detector.

The submersible vehicle also includes a propulsion unit 75, a compartment for operators 77 and a second compartment 79 for the associated electronics and data analyzer. The vehicle can proceed underwater to locations where minerals are suspected to occur. Projections 71 and 73 can penetrate into the surface sediment while the vehicle rests on the ocean floor and readings are taken. The submersible may then be easily moved to examine numerous other locations.

A mineral-detection apparatus has been described for marine mineral exploration. The apparatus is kept mobile by use of a small size but high yield ^{252}Cf neutron source. This source irradiates a large sample of geologic strata to produce high-energy capture gamma radiation with minimum interfering gammas from inelastic scattering. A gamma radiation detector of high-energy resolution defines capture gamma spectra signatures with sufficient accuracy to identify minerals in the presence of activated sodium and chlorine as well as other background radiation occurring beneath the ocean surface.

We claim:

1. A marine mineral-detection apparatus which comprises, in combination:

A. a first and a second housing member each having a generally spherically shaped portion and a projection of reduced diameter extending therefrom, and structural means for supporting said housing members in fixed

spaced relationship with said projections of reduced diameter pointed towards a common direction in axially parallel alignment;

B. a neutron source unit disposed in said first housing member including

1. a ^{252}Cf neutron source,

2. hydrogenous shielding material disposed in the generally spherically shaped portion of said first housing member, and

3. extensible means for supporting said ^{252}Cf neutron source in a retracted position near the center of said hydrogenous shielding material, and in an extended position within said projection of reduced diameter of said first housing member to bombard surrounding geologic strata with neutrons;

C. a prompt gamma ray detector unit disposed in said second housing member including

1. a Li-drifted Ge crystal supported within the projection of reduced diameter of said second housing member for producing electrical pulses in response to prompt gamma radiation from mineral values within said geologic strata,

2. means disposed in the generally spherically shaped portion of said second housing member for cooling said detector, and

3. neutron-absorbing material disposed between said Li-drifted Ge crystal and said neutron source.

2. The apparatus of claim 1 wherein said neutron source unit includes a sealed elongated vessel, containing said extensible means and said ^{252}Cf neutron source, mounted within said first housing member and extending into said projection of reduced diameter.

3. The mineral-detection apparatus of claim 1 wherein said cooling means includes

a. a closed reservoir of liquid refrigerant for cooling said crystal; and

b. pressure relief valves within the walls of said reservoir and said second housing member for discharging refrigerant gas and for maintaining said second housing at a pressure slightly greater than ambient pressure.

4. The mineral detection apparatus of claim 1 wherein said ^{252}Cf neutron source is encapsulated in a material selected from the group consisting of tantalum, niobium, zirconium and alloys thereof.

* * * * *

United States Patent [19]

Takahashi et al.

[11] **Patent Number: 4,954,706**

[45] **Date of Patent: Sep. 4, 1990**

[54] **RADIOGRAPHIC IMAGE PICKUP APPARATUS**

[75] Inventors: **Tetsuhiko Takahashi**, Tokyo; **Kenichi Okajima**, Hoya; **Hiroshi Takeuchi**, Matsudo, all of Japan

[73] Assignee: **Hitachi, Ltd.**, Tokyo, Japan

[21] Appl. No.: **330,495**

[22] Filed: **Mar. 30, 1989**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 181,694, Apr. 14, 1988.

[30] **Foreign Application Priority Data**

Apr. 1, 1988 [JP] Japan 63-78009

[51] **Int. Cl.**[5] **G03B 42/00**

[52] **U.S. Cl.** ..... 250/327.2; 250/484.1; 250/213 R

[58] **Field of Search** ..... 250/327.2, 484.1, 213 R

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4,554,453	11/1985	Feigt et al.	250/213 R X
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Primary Examiner—Constantine Hannaher
Assistant Examiner—J. Eisenberg
Attorney, Agent, or Firm—Antonelli, Terry, Stout & Kraus

[57] **ABSTRACT**

A radiographic image pickup apparatus for diagnosis using an image detector in which a phosphor layer for converting an X-ray image into an optical image, a photoconductive layer for storing an optical image as a latent image, light-emitting means for exciting the photoconductive layer segment by segment are laminated into a plate form, wherein one of the electrodes sandwiching the photoconductive layer and the light-emitting means are respectively divided into array-formed elements in directions orthogonal to each other, and an element selection circuit for successively selecting these elements and reading out said latent image in time sequential electric signal is formed integrally on the substrate of the image detector.

6 Claims, 9 Drawing Sheets

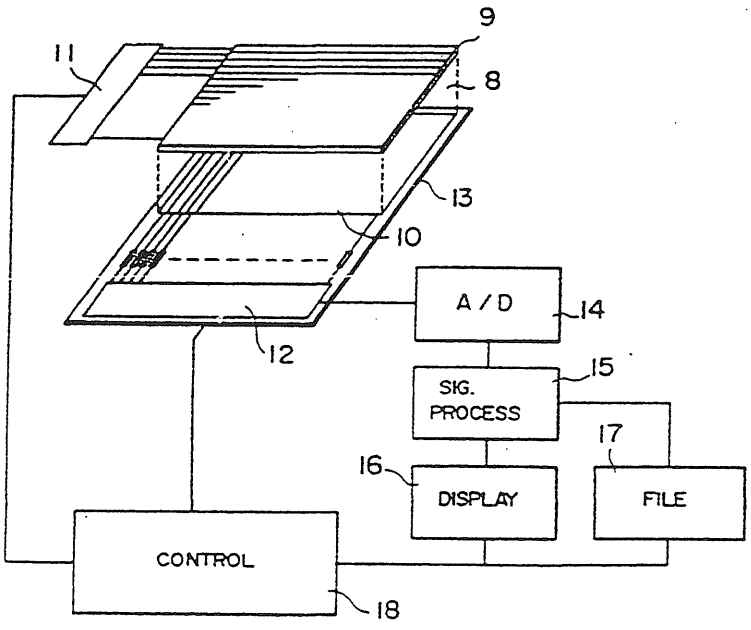
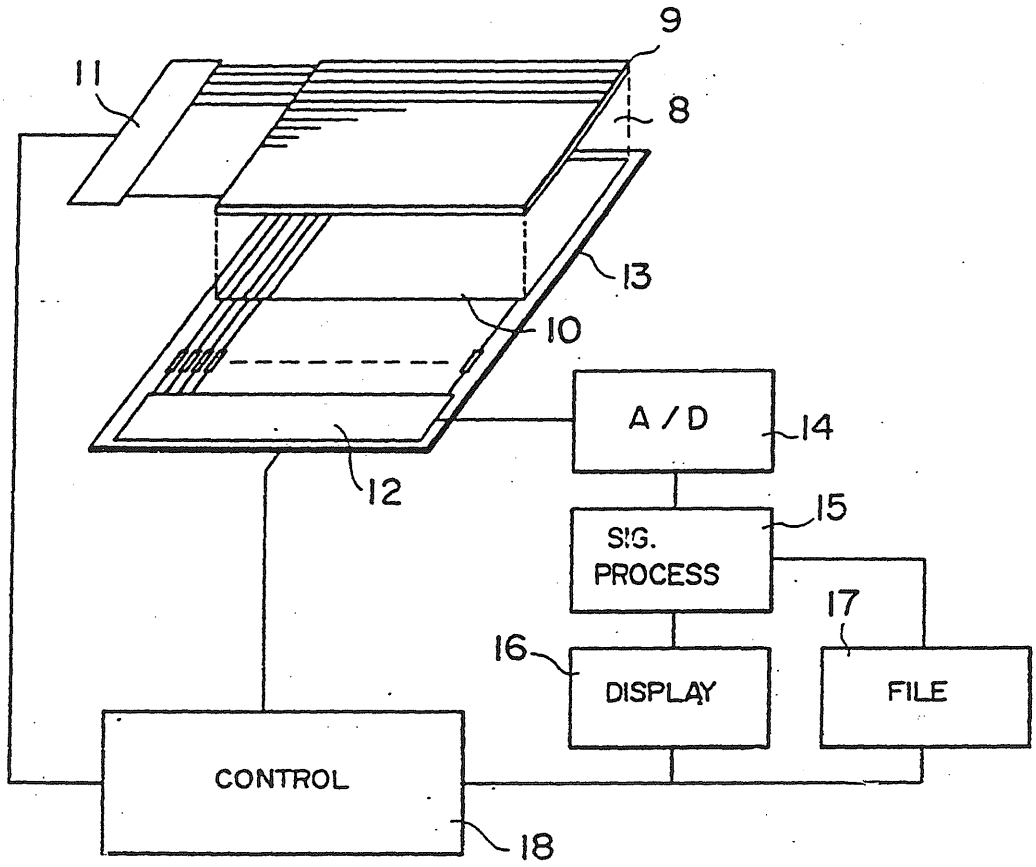


FIG. 1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11
8
13
10
A / D
14
12
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SIG.
PROCESS
17
16
DISPLAY
FILE
CONTROL
18

FIG. 2

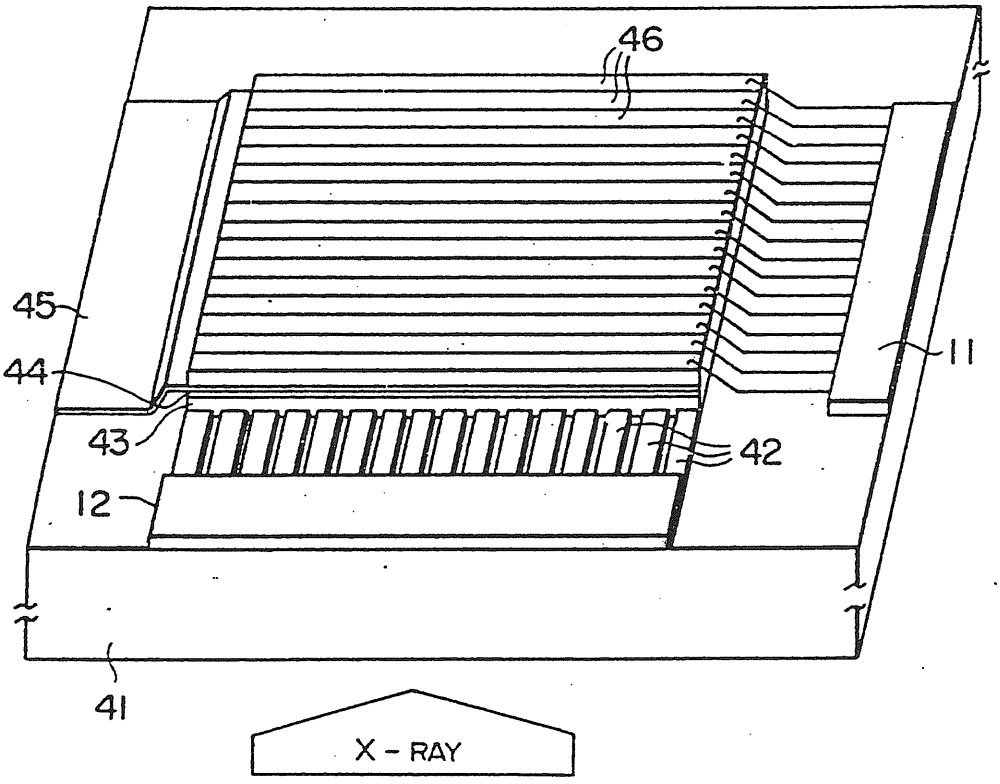
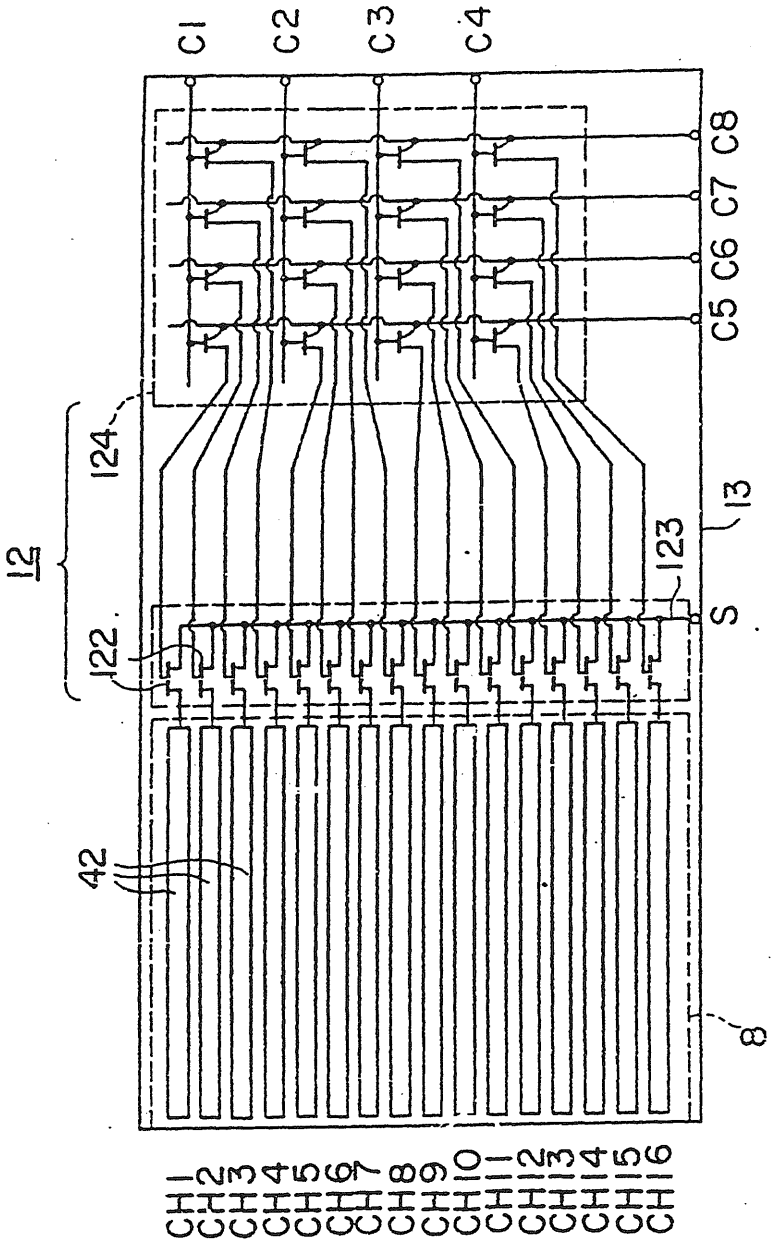


FIG. 3


C1
C2
C3
C4
C5
C6
C7
C8
124
12
122
13
123
S
42
8
CH1
CH2
CH3
CH4
CH5
CH6
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CH13
CH14
CH15
CH16

FIG.4A

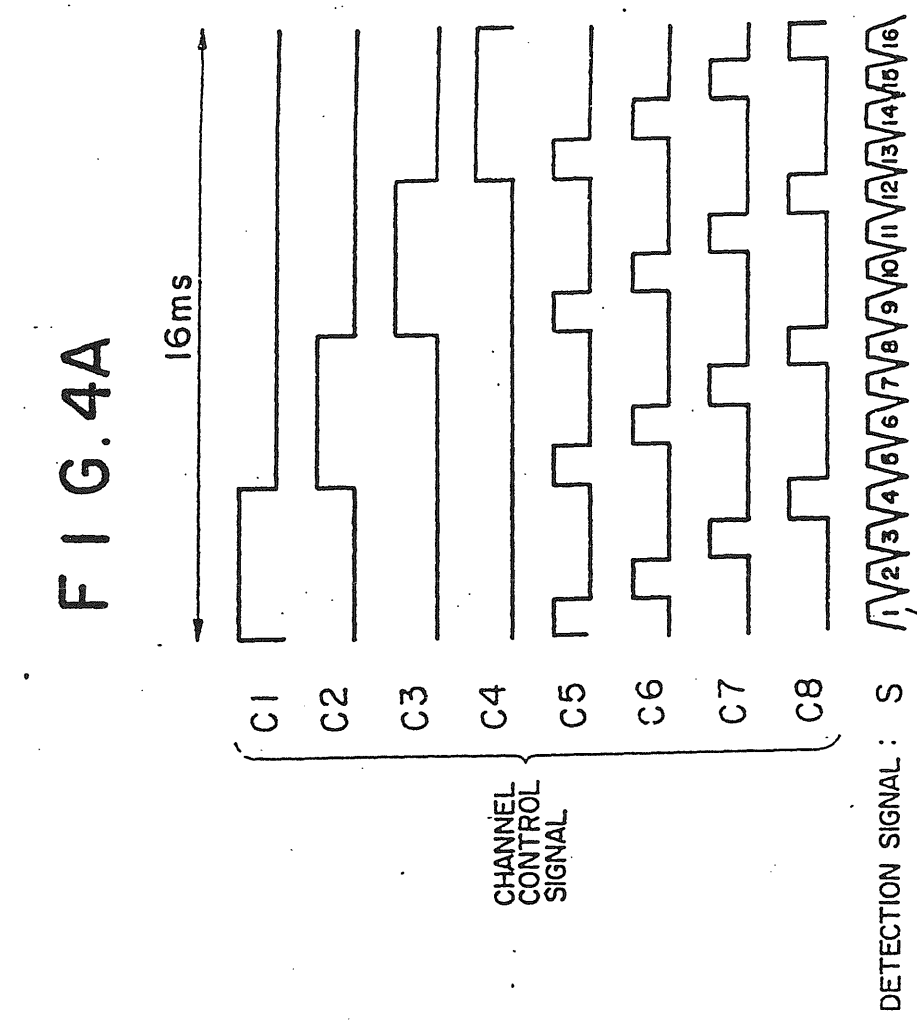

16ms
C1
C2
C3
C4
C5
C6
C7
C8
CHANNEL CONTROL SIGNAL
DETECTION SIGNAL : S
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
CHANNEL NO.

FIG. 4B

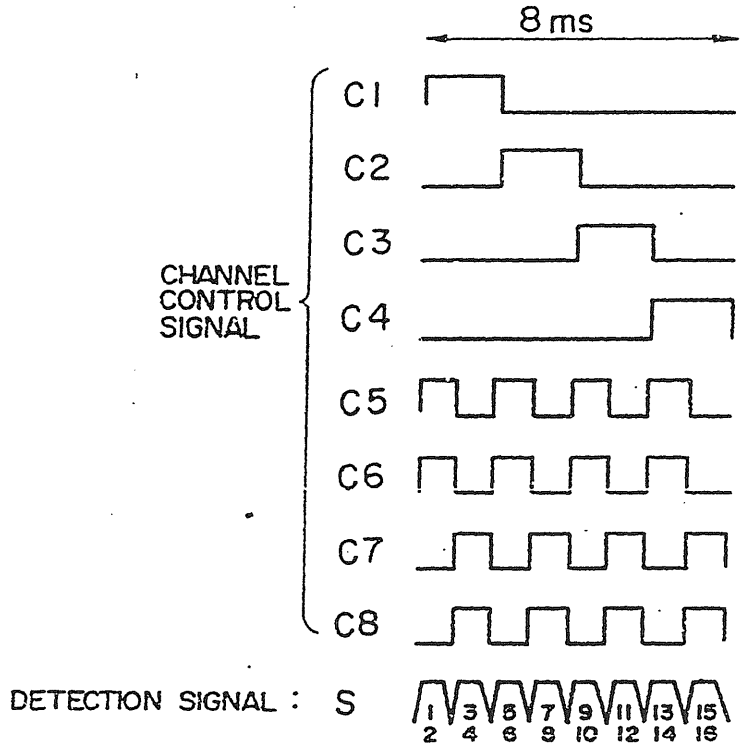

8 ms
CHANNEL CONTROL SIGNAL
C1
C2
C3
C4
C5
C6
C7
C8
DETECTION SIGNAL : S
1 3 5 7 9 11 13 15
2 4 6 8 10 12 14 16

FIG. 5

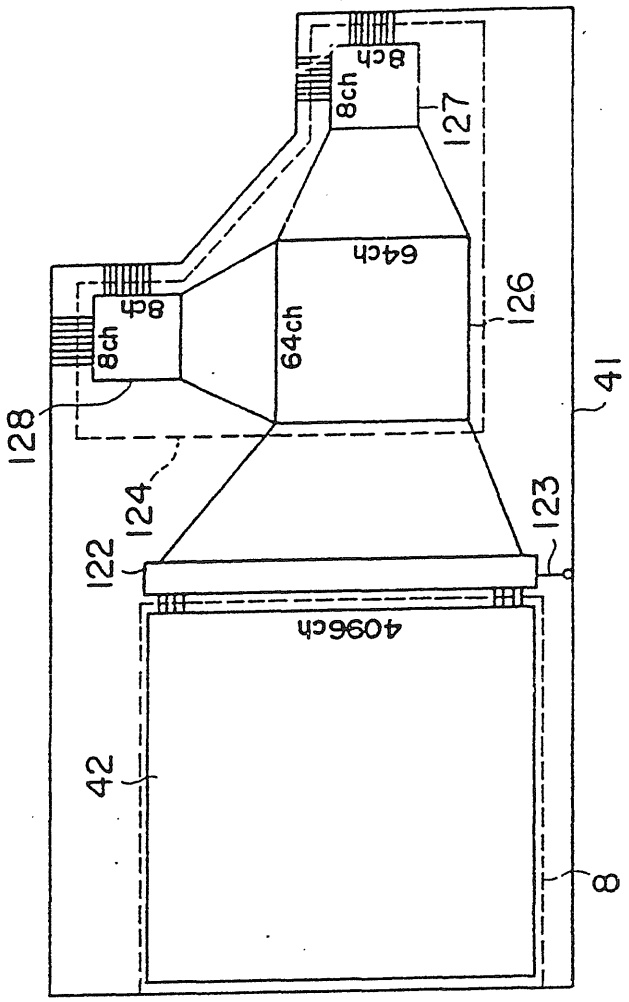
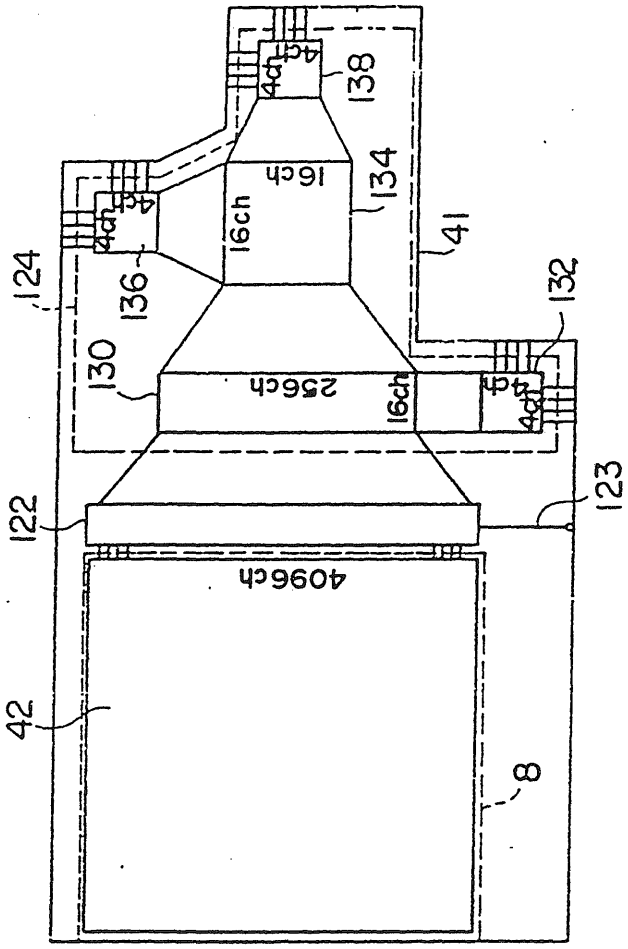


FIG. 6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16ch
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16ch
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4ch
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4ch
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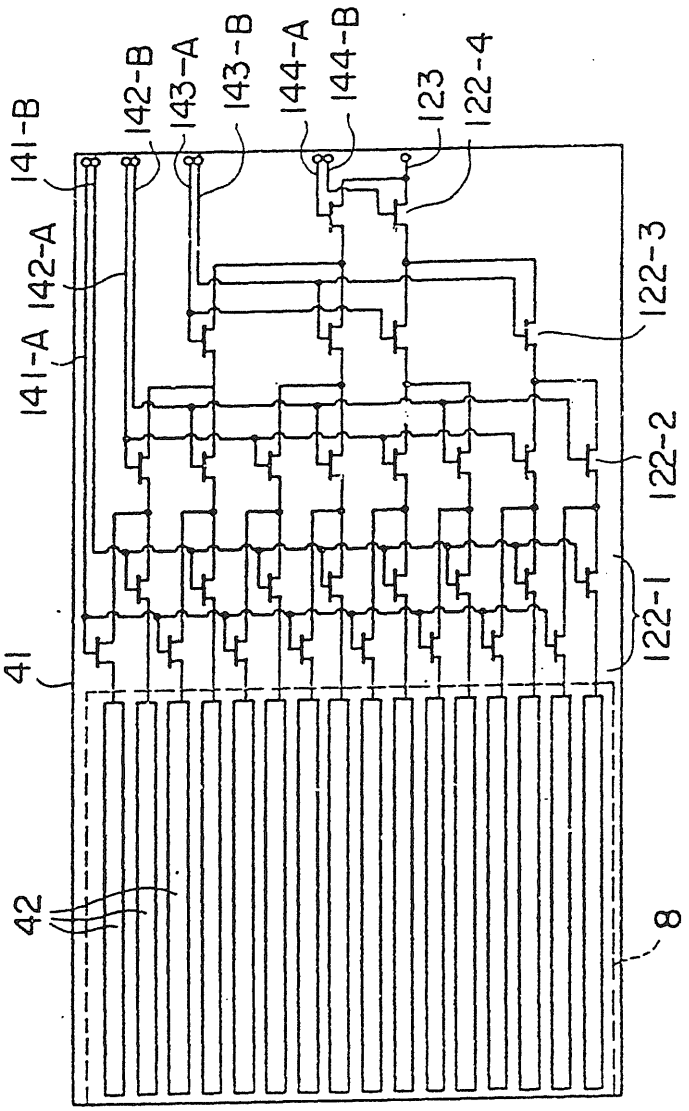
122
4096ch
42
8

FIG. 7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122-2
122-1
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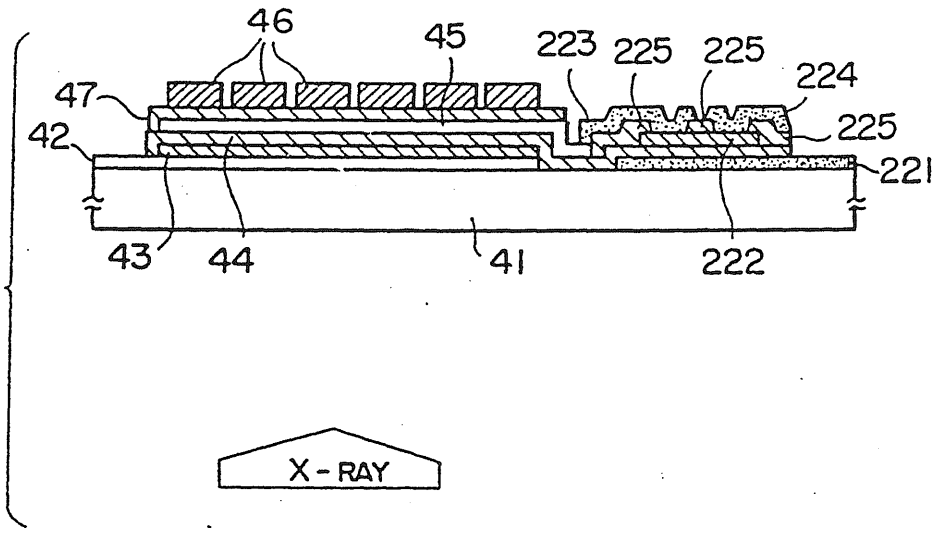
42
8

FIG. 8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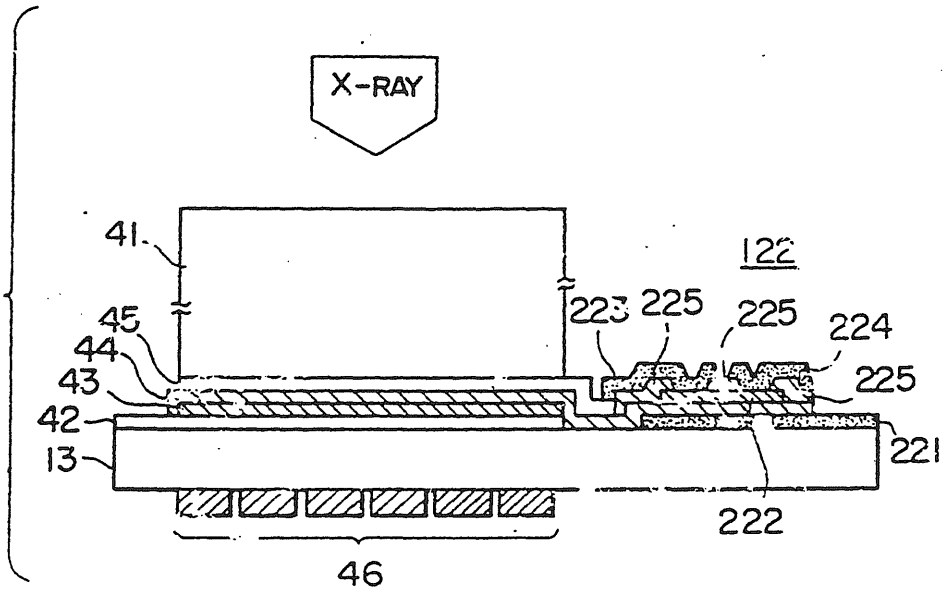
41
222
X-RAY

FIG. 9


X-RAY
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122
223
225
225
224
45
44
43
225
42
221
13
222
46

RADIOGRAPHIC IMAGE PICKUP APPARATUS

CROSS REFERENCE TO THE RELATED APPLICATION

This application is a continuation-in-part application of U.S. patent application, Ser. No. 181,694 filed on Apr. 14, 1988.

BACKGROUND OF THE INVENTION

1. FIELD OF THE INVENTION

This invention relates to an image pickup apparatus adapted for use in medical radiodiagnostics, and more particularly to a plate-shaped image pickup device for receiving a radiographic image and transforming the image into an electric signal sequence.

2. DESCRIPTION OF THE RELATED ART

U.S. Pat. No. 4,535,468 discloses a photographic apparatus for medical use with a three-layer system lying between two electrodes, to which a d-c voltage is applied. The two outer layers are photoconductors and the middle layer consists of a material in which charge carriers can be stored. An image radiated from one side can be read out from the other side in the form of an electric pulse sequence by scanning using a light beam and can be reproduced on a television screen.

U.S. Pat. No. 4,268,750 discloses an analogous photographic apparatus having a multi-layer detector including only one photoconductive layer.

The detector of these apparatuses has a pair of parallel plate electrodes sandwiching the photoconductive layer and one signal line connected thereto. The latent image once stored in the detector in the form of a charge distribution is read out as a time sequential signal by scanning a spot-shaped laser beam.

In the solid state image pickup elements, i.e. photographic sensors such as CCD cameras or MOS image pickup devices, electronic pixel selection means is adopted. This selection means is integrated on the one-chip semiconductor substrate together with the pixels. These image pickup devices, however, have extremely low sensitivity to the X ray for medical use range, and hence cannot be directly used as the X ray image pickup apparatus for medical use. Further, the image pickup apparatus for medical use requires a number of pixels as many as 4000^2 at the maximum and an image plane size as wide as 40 cm $\times$ 40 cm at the maximum. Thus, the techniques of the above-mentioned photographic image pickup devices (typically, having a number of pixels around 600^2 and an image plane size of 2 inches ϕ or less) cannot be used.

SUMMARY OF THE INVENTION

In the above-mentioned prior art, the capacitance formed between the two electrodes connected to a signal line is large and hence results in a lowering of the signal-to-noise ratio. Further, the mechanism of scanning a laser beam on a image pickup field forms a large factor of making the device big and complicated.

An object of this invention is to provide a radiographic image pickup apparatus which suppresses the mixing of noise into the time sequential electric signals.

Another object of this invention is to provide a radiographic image pickup apparatus having electronic pixel selection means compactly integrated with the detector, thereby raising the reliability and largely reducing the cost.

A of this invention includes dividing one of the electrodes sandwiching the photoconductive layer into array form, providing selection means for successively selecting the divided electrodes one by one, and forming this selection means on the substrate of the detector by stacking layers using thin film technology.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of the general construction of an embodiment of this invention.

FIGS. 2 and 3 are a perspective view and a plan view showing a main part of the embodiment.

FIGS. 4A and 4B are time charts for illustrating the operation of the embodiment of FIG. 3.

FIGS. 5, 6 and 7 are plan views respectively showing other embodiments.

FIGS. 8 and 9 are cross-sections showing still other embodiments.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Now, description will be made, referring to FIGS. 1 and 2.

FIG. 1 is a conceptual diagram of the whole radiographic image pickup apparatus. A radiographic image storing unit 8 has typical dimensions of 40 cm $\times$ 40 cm. This is an image plane size required for diagnosing the breast. This radiographic image storing unit 8 includes a photoconducting layer and is in close optical contact with a phosphor plate (not shown). The X ray image is converted into a light image by the phosphor plate. The image storing unit 8 stores charge distributions corresponding to the light image as a latent image. Further, on the image storing unit 8, an exciting unit 9 and a reading unit 10 are laminated. The exciting unit 9 and the signal reading unit 10 have respectively one dimensional disposition and are orthogonal to each other. Designation of a position on an image plane is performed by the combination of the respective addresses of the exciting unit 9 and the reading unit 10. These channel designations are done by channel designation units 11 and 12. The signal from the reading unit 10 is successively A/D converted in an A/D converter 14 while being controlled by the channel designation unit 12. This signal is processed by a signal processing unit 15, displayed in an image display unit 16, and stored in an image file unit 17. Numeral 18 denotes a control unit for controlling the various units.

FIG. 2 shows details of an example of the radiographic image storing unit 8, the exciting unit 9, and the reading unit 10. Firstly, the structure will be explained. A phosphor plate 41 is a ceramic scintillator formed, for example, of $CdWO_4$ or Gd_2O_2S and serves also as a substrate 13 which is shown in FIG. 1. On the phosphor plate 41, are laminated an electrode layer 42, a photoconductive layer 43, an insulating layer 44, and another electrode layer 45. The photoconductive layer 43 is formed, for example, of a layer of amorphous selenium (a-Se) or a laminate of a-Se/a-Si, of for example 2 μm thickness. This corresponds to the above-mentioned storing unit 8. The pair of electrodes 42 and 45 sandwiching the photoconductive layer 43 are formed of transparent conductive material, for example SnO_2, ITO (indium-tin-oxide), SnO_2/ITO or Au. The electrode layer 42 on the substrate side is divided into one-dimensional array electrodes. FIG. 2 shows an example in which 16 channel electrodes are disposed in an array form. In a preferable disposition for medical radio-

graphic diagnosis, the channel width is 100 μm, and the number of channels is 4096. These array-form electrodes correspond to the reading unit 10 in FIG. 1.

The insulating layer 44 is formed, for example, of Sb_2S_3, CeO_2, SiO, SiO_2, MgF or an organic insulating film. On the electrode layer 45, are provided stripe shaped light-emitting material rows 46 which are disposed perpendicular to the electrodes 42. These correspond to the exciting unit 9 of FIG. 1. The light emitting material 46 may be formed of an EL (electroluminescent) light-emitting material or a plane-light-emitting LED (light emitting diode). Although the figure shows 16 light-emitting material rows, in a preferable disposition for medical radiographic diagnosis, 4096 stripe-shaped light-emitting material rows, each having a channel width of 100 μm are disposed. In the case of the number of electrodes being 4096 and the number of light-emitting material rows being 4096, the vertical and the horizontal lengths of the image plane sensor and 40.96 cm and the spatial resolution is 5 lp/mm. In the present structure, the X ray image is irradiated on part of the rear surface of the phosphor plate 41, more specifically on a region corresponding to the region where the photoconductive layer 43 is formed. Therefore, the X ray is not irradiated on the channel designation units 11 and 12.

Next, the operation principles will be explained. First, a voltage V is applied between all the elements of the electrode 42 and the electrode 45, causing all the elements of the light-emitting material unit 46 to emit lights. By this action, charge is uniformly induced at the interface formed between the photoconductive layer 43 and the insulating layer 44. Then, the light-emitting elements are turned off to terminal the excitation. Then, a voltage-V' having the opposite polarity to that of the previously applied voltage is applied between the electrodes. In this state, an X ray image is injected to the phosphor layer 41. The X ray image is converted into a light image by the phosphor layer 41. This light image transmits the transparent electrode 42 and is incident on the photoconductive layer 43. At this moment, the previously induced charge is discharged in accordance with the amount of incident light. As a result, a charge pattern reflecting the incident X ray image is formed at the interface between the photoconductive layer 43 and the insulating layer 44. This is the latent image. After the termination of irradiation of X ray, the reading of the latent image is performed. For this purpose, one of the light-emitting segments 46 is designated by the channel designating unit 11 to emit light. In this state, a voltage V identical to the firstly applied voltage is applied between one of the electrodes 42 and the electrode 45. Here, in a small area (one picture element) where a selected light-emitting segment and a selected electrode cross to each other, the charge flowing from the electrode 42 to the photoconductive layer 43 is equal to the amount of charge discharged upon irradiation of the X ray image and hence represents the image information of the picture element. By the successive selection of the electrodes 42, the image information for one line is successively read out. Then, the selection of the light-emitting element 46 is changed and similar scanning is successively performed to read out the X ray image as time sequential electric signals.

Next, the signal reading unit will be explained in detail referring to FIG. 3. The figure illustrates the case where the signal detecting one-dimentional electrode has 16 channels. The respective electrodes are connected to one signal line 123 through respective thin film transistors (hereinafter abbreviated as TFT) 122 formed on the substrate 13, i.e. the phosphor plate 41 in the structure of FIG. 2. The arbitrary on/off of the gate signal of the TFTs is possible by a TFT circuit 124 of 4 ×4 configuration formed on a different portion of the substrate 13. This TFT matrix serves as a channel controlling unit. Eight signal lines from the exterior of the substrate are used for controlling this matrix.

FIGS. 4A and 4B show an example of a signal deriving sequence in the present structure. FIG. 4A illustrates a mode (16 channel mode) in which the signals on 16 channel reading electrodes are successively read out channel by channel, whereas FIG. 4B illustrates 8 channel mode in which signals are read out 2-channels by 2-channels. In the latter case, the image fetching at twice the speed as that for the 16 channel mode is possible. This is a high speed low resolution image fetching. This is effective for X ray transmission diagnosis. The 16 channel mode is of low speed but has a high resolution and functions as the picture-taking mode.

FIG. 5 shows the image reading in the case of 4096 channels. A controlling TFT circuit 124 for applying control signals to the gates of 4096 selecting TFTs 122 includes a 64 ×64 matrix 126 and two 8 ×8 matrices 127 and 128 for controlling the 64 ×64 matrix. Each of these matrices has a similar structure as the matrix shown in FIG. 1. With these matrices, the control of 4096 channels can be made with 32 control lines.

FIG. 6 illustrates another matrix disposition for the case of 4096 channels. In this case, the controlling TFT circuit for supplying control signals to the gates of 4096 selection TFTs 122 comprises a 16 ×256 TFT matrix 130, a 4 ×4 TFT matrix 132 for performing row selection of the matrix 130, a 16 ×16 TFT matrix 134 for performing column selection of the matrix 130, and two 4 ×4 TFT matrixes 136 and 138 for performing row and column selections of the matrix 134, respectively. In this structure, mode selection among fine modes of 256 channel mode, 512 channel mode, 1024 channel mode, 2048 channel mode, and 4096 channel mode, by the change in the selection sequence of the matrix 132.

FIG. 7 illustrates another example of the selecting TFT circuit 122. This example illustrates a structure having a 16 channel reading electrode array 42, for enhancing understanding. The signals on the respective channel electrodes are connected to one signal line 123 through a first stage selection TFT column 122-1, a second stage selection TFT column 122-2, a third stage selection TFT column 122-3, and a fourth stage selection TFT column 122-4. The gates of 16 selection TFTs of the first stage are connected alternately to control lines 141-A and 141B. Similarly, the gates of selection TFTs in the second stage are connected to control lines 142-A and 142-B, the gates of selection TFTs in the third stage are connected to control lines 143-A and 143-B, and the gates of selection TFTs in the fourth stage are connected to control lines 144-A and 144-B. This construction establishes a binary decoder. Selection of each one of four pairs of control lines selects one channel. Alternate selection of the respective pairs performs sequential selection of 16 channels, realizing a 16 channel mode. The successive selection of 8 channel mode can be realized by making the both of the first pair of control lines 141-A and 141-B always on and alternately selecting the remaining pairs of control lines.

FIG. 8 shows a cross-section of the structure of another embodiment of this invention. This embodiment

differs from the embodiment shown in FIG. 2 in the point that of the electrodes 42 and 45, the upper electrode 45 is divided into one-dimensional array form and the lower electrode 42 is uniform. Other reference numerals denote similar parts as in FIG. 2. Numeral 47 denotes a transparent protection film laminated on the electrode 45. Further, on a scintillator plate 41 of FIG. 8, channel designating units 10 and 12 are formed. In the figure, however, only a selecting TFT 122 of the channel designating unit 10 is shown. The TFT 122 is formed by successively laminating an Al electrode 221 which forms a gate, an insulating layer 44, and an amorphous silicon layer 222. A source electrode 223 formed of an Al layer is connected to a reading electrode 45. A drain electrode 224 similarly formed of an Al layer is connected to a signal line common to the respective channels. Numeral 225 denotes an insulating layer separating the electrodes.

FIG. 9 shows another embodiment. In this embodiment, a scintillator plate 41 is not used as a substrate and a separate transparent substrate 13 formed of a glass plate is used. The image storing unit and TFT 122 have similar structures as those in FIG. 8, but are successively laminated on one surface of the glass substrate 13. On the electrode 45, a scintillator 41 is laminated. Further, on another surface of the glass substrate, an LED array 46 is provided.

In each of the embodiments as explained above, at least the photoconductive layer and the electrode layers sandwiching the photoconductive layer are formed on one substrate in an integrated laminate, and thin film transistors for selecting the electrode array are formed on a different region of the substrate than the region irradiated by the X-ray. It is only required for the exciting light-emitting means 46 in the structures of FIGS. 2 and 8, or the light-emitting means 46 and the phosphor plate 41 in the structure of FIG. 9, to be optically coupled with the photoconductive layer. They may not have an integrated structure.

Further, as the image storing unit, one including two phosphor layers as shown in U.S. Pat. No. 4,535,468 may be used.

We claim:

1. A radiographic image pickup apparatus comprising:

a phosphor layer for converting a radiographic image into an optical image;

at least one photoconductive layer optically coupled with said phosphor layer;

a first and a second electrode sandwiching said photoconductive layer, at least one of the first and the second electrodes being divided into one-dimensional array-formed elements aligned in a first direction;

a substrate on which at least said photoconductive layer and said first and second electrodes are integrated in one body;

exciting light-emitting means optically coupled with said photoconductive layer, said exciting light-emitting means being divided into one-dimensional array-formed elements aligned in a second direction orthogonal to said first direction;

selection means for selectively connecting respective elements of one of said one-dimensional array-formed elements to one signal line, wherein said selection means is formed on said substrate in a region which is not exposed to said radiographic image.

2. A radiographic image pickup apparatus according to claim 1, wherein said phosphor layer is a plate-shaped phosphor member and serves also as said substrate.

3. A radiographic image pickup apparatus according to claim 1, wherein said substrate comprises an optically transparent member having a first surface on which said photoconductive layer and said first electrode are laminated, and a second surface opposed to the first surface, on which said exciting light-emitting means is stacked.

4. A radiographic image pickup apparatus, according to claim 1, wherein said selection means comprises a plurality of selecting thin film transistors formed on said substrate to connect said signal line and the respective elements of said array-formed elements, and a control circuit for controlling the gates of said selecting thin film transistors.

5. A radiographic image pickup apparatus according to claim 4, wherein said control circuit includes thin film transistors disposed in a matrix, and the gate of a desired selecting thin film transistor is selected by the selection of a row line and a column line of the matrix.

6. A radiographic image pickup apparatus according to claim 1, wherein said selecting means comprises a plurality of thin film transistors for selectively connecting one signal line and at least one of said array formed elements.

* * * * *

US005440129A

United States Patent [19]

Schmidt

[11] Patent Number: 5,440,129

[45] Date of Patent: Aug. 8, 1995

[54] DETECTOR FOR HIGH-ENERGY RADIATION

[75] Inventor: Martin Schmidt, Emskirchen, Germany

[73] Assignee: Siemens Aktiengesellschaft, Munich, Germany

[21] Appl. No.: 283,192

[22] Filed: Aug. 4, 1994

[30] Foreign Application Priority Data

Oct. 11, 1993 [DE] Germany 43 34 594.8

[51] Int. Cl.[6] G01T 1/20; G01T 1/24

[52] U.S. Cl. 250/366; 250/368; 250/370.11

[58] Field of Search 250/366, 367, 368, 370.11

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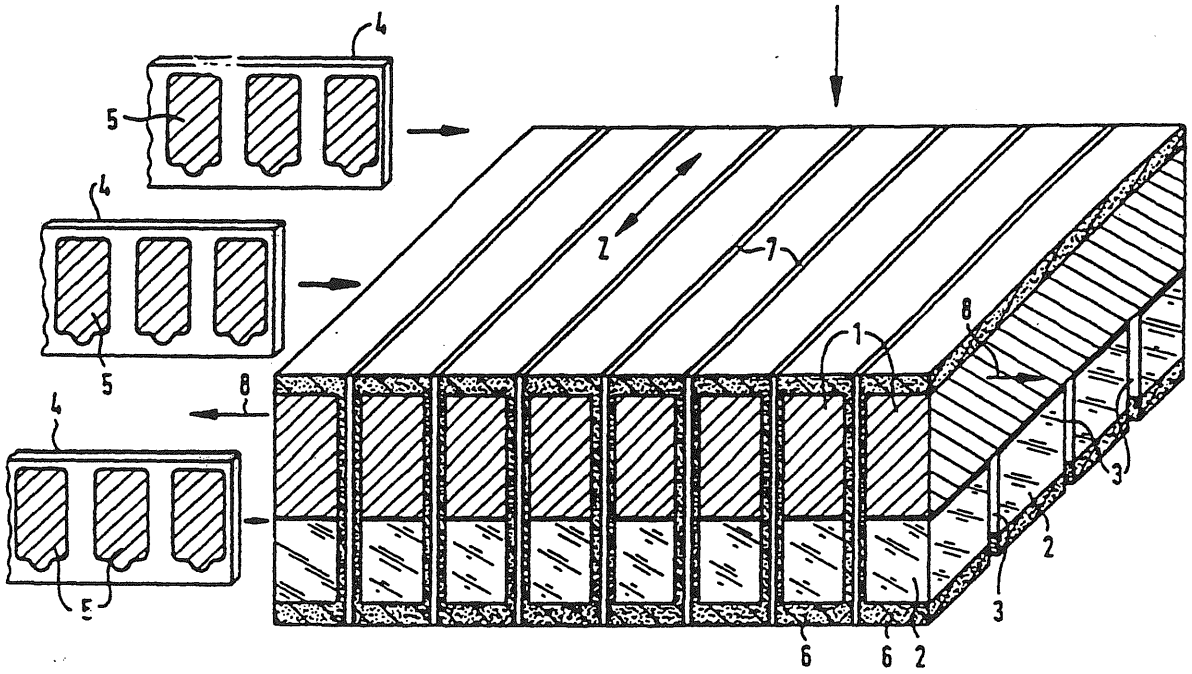
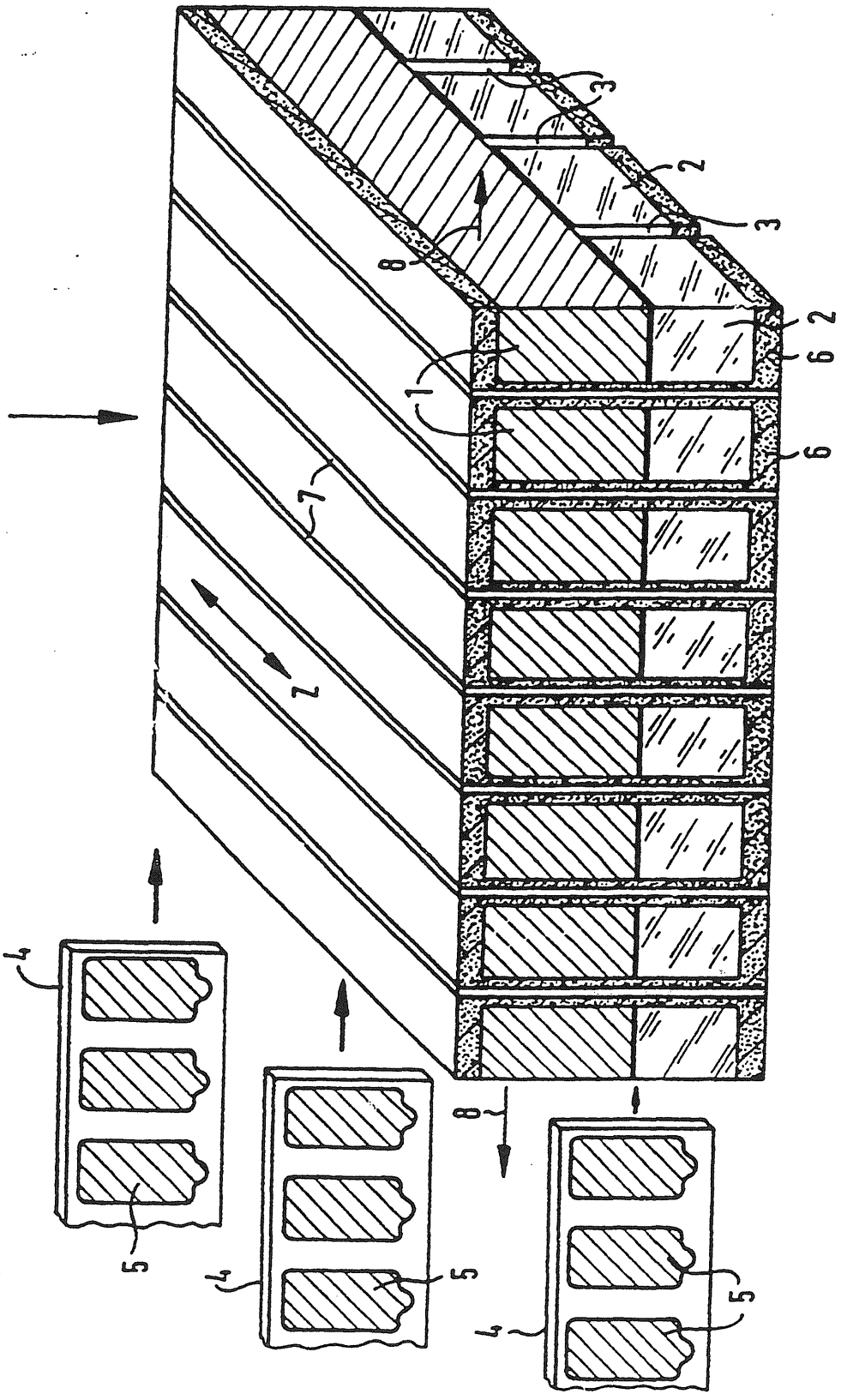
Primary Examiner—Constantine Hannaher
Assistant Examiner—Edward J. Glick
Attorney, Agent, or Firm—Hill, Steadman & Simpson

[57] ABSTRACT

A detector for computer tomography or digital radiography has an optimum efficiency and an optimum signal-to-noise ratio, and the thickness of the acquired x-ray beam can be selected in a simple way. The detector is formed by a row of parallel, bar-shaped scintillators. Every scintillator has a row of optical conductors extending in the longitudinal direction of the scintillator allocated to it. The optical conductors of a scintillator are separated from one another by slots, with the slots between the optical conductors of neighboring scintillators being in registry. Chips carrying photodiodes are plugged into the slots. Every scintillator together with the allocated optical conductors is surrounded by a reflector.

5 Claims, 1 Drawing Sheet

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DETECTOR FOR HIGH-ENERGY RADIATION

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention is directed to a detector for high-energy radiation of the type used in a computed tomography apparatus or digital radiography.

2. Description of the Prior Art

Detectors for high-energy radiation are known that are composed of a series connection of scintillators and photodiodes. Each detector has one scintillator and a maximum of two photodiodes disposed in successive planes as viewed in the radiation propagation direction. Such detectors are employed, for example, in computed tomography.

SUMMARY OF THE INVENTION

An object of the invention is to provide a detector of the type initially cited that is optimum in view of efficiency and signal-to-noise ratio, and with which it is possible to optionally acquire individual, thin x-ray beams, or a plurality of thin x-ray beams lying behind one another, or thick x-ray beams.

The above object is achieved in a detector for computer tomography or digital radiography constructed in accordance with the principles of the present invention, formed by a row of parallel, bar-shaped scintillators, each scintillator having a row of optical conductors allocated thereto, extending in the longitudinal direction of the scintillator. The optical conductors of each scintillator are separated from each other by slots, with the slots between the optical conductors of neighboring scintillators being in registry. Chips carrying photodiodes are plugged into the slots. Each scintillator and its allocated optical conductors are surrounded by a reflector.

DESCRIPTION OF THE DRAWINGS

The single figure is a perspective view, partly in section, of a detector for high-energy radiation constructed in accordance with the principles of the present invention, illustrating the manner of insertion of photodiode-carrying chips into a detector module.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The drawing shows a module of a detector for high-energy radiation, particularly x-radiation. The radiation is incident on the module from above. The module has a series (row) of bar-shaped scintillators 1 lying parallel to one another. A row of optical conductors 2 is in optical contact with every scintillator 1. The optical conductors 2 are separated from one another by slots 3. The slots 3 between the optical conductors 2 of neighboring scintillators 1 are in registry, so that it is possible to insert chips 4 into the slots 3 of the illustrated module, a series (row) of photodiodes 5 being applied on each such chip 4. Every photodiode 5 is consequently in optical contact with an optical conductor 2. Every scintillator 1 with the allocated optical conductors 2 is surrounded by a reflector 6.

Tapping the signals of the photodiodes 5 can ensue by means of a printed circuit board (not shown) at the underside of the module. The sub-signals of the photodiodes 5 of a scintillator 1 can thereby be interconnected, so that a relatively large slice thickness of the acquired x-ray beam arises. The sub-signals, however, can also be individually evaluated, so that a plurality of parallel slices of an x-ray beam can be acquired. Given a thin slice, only one sub-signal can also be acquired and evaluated.

The following are suitable as materials for the reflectors 6 epoxy glues filled with titanium oxide or with lead (11) hydroxy carbonate in arbitrary mixing ratios. An optimum optical decoupling is achieved when reflective metallic layers 7 are respectively arranged between two scintillators 1 with the allocated optical conductors 2.

The optical conductors 2, which are arranged directly under the scintillators 1, should be largely matched to the scintillation material in terms of their refractive index and in terms of their thermal expansion. Thus, glass having a high refractive index is advantageous for use with scintillator 1 of $CdWO_4$, GYO and Gd_2O_2S. Optical plastics are suitable for scintillators 1 of luminescent foils and cesium iodide. It is advantageous to fashion the outermost optical conductors 2 somewhat longer in the Z-direction than the allocated scintillator 1, in order to compensate a signal drop at the end of the scintillator 1.

The number of photodiode rows, i.e. of chips 4, is arbitrary. Given a single-sided arrangement of the photodiodes 5 on a silicon chip, the back side is mirrored for optical reasons. When a metallic mirroring is selected, this can simultaneously form the ground contact for the photodiodes. The employment of two photodiodes per layer (or slice) is advantageous for reasons of light energy, whereby these photodiodes can be applied by vapor deposition in an a-Si technique on a thin glass substrate at the front and back side. Fundamentally, the thickness of the photodiode row should be as small as possible, for example 100 μm. The active surfaces of the photodiodes 5 cover the ends of the optical conductors, whereby the active surface of a photodiode 5 can be of practically the same size as the exit face of the optical conductor 2, this being advantageous in view of the light yield.

Given the illustrated detector, the signals from the slices having the allocated photodiodes 5 can be individually calibrated. Differences in the homogeneity of the material in each slice can thus be individually measured and can also be corrected, even when the output signals of a plurality of thin slices of the x-radiation are combined to form a thick slice of the x-radiation.

The photodiodes 5 have substantially no x-radiation incident thereon, so that direct conversion in the silicon does not occur; this would lead to elevated noise and would lead to image errors in that case wherein the output signals of the photodiodes 5 serve the purpose of image generating.

A further advantage of the illustrated detector is the small diode area, even given a large number of chips 4 and long Z-lengths. A small diode area results in a low capacitance of the photodiodes 5 and a low dark current. This is important for the signal gain since the capacitance and the dark current influence the electronic noise in the amplifier.

The illustrated module of a detector of the invention is composed of eight channels. Modules having a different channel number, for example with 4, 16 or 32 channels are also possible. A plurality of such modules can be united to form a radiation-electrical transducer for imaging in computer tomography or in digital radiography, such that all scintillators of the modules lie in series

parallel to one another. A plurality of such modules are thus connected to one another in the direction of the arrows 8.

The modular structure is advantageous for economical reasons. Thus, individual modules that do not meet the specification or fail during operation can be replaced.

A further advantage of this arrangement is that the noise in thin slices is lower than currently known detectors. When, given thin slices, only one or two photodiodes are driven to collect light, the capacitive noise part and the noise part in the image caused by dark current are lowered. Given a higher signal, i.e. a thicker slice, photodiodes are correspondingly added in. The noise part in the image always remains proportionally identical.

Although modifications and changes may be suggested by those skilled in the art, it is the intention of the inventor to embody within the patent warranted hereon all changes and modifications as reasonably and properly come within the scope of his contribution to the art.

I claim as my invention:

1. A detector for high-energy radiation comprising:

a row of parallel, bar-shaped scintillators, each scintillator having a longitudinal direction;

a row of optical conductors for each scintillator, wherein each row of optical conductors extends in said longitudinal direction and is in optical contact with a respective scintillator, said optical conductors of each row being separated from each other by slots, with the slots between the optical conductors of neighboring scintillators being in registry;

a plurality of chips, each chip having photodiodes thereon, respectively disposed in said slots with each photodiode being in optical contact with an optical conductor; and

a reflector surrounding each scintillator and the optical conductors in optical contact therewith.

2. A detector as claimed in claim 1 further comprising a metallic layer disposed between neighboring reflectors.

3. A detector as claimed in claim 1 wherein each chip comprises a silicon chip carrying a row of photodiodes on one side thereof, and carrying a reflective metal layer on an opposite side thereof, said reflective metal layer comprising a ground contact for said photodiodes.

4. A detector as claimed in claim 1 wherein each chip carries respective rows of photodiodes on both sides thereof.

5. A detector as claimed in claim 1 wherein each chip comprises a glass carrier, and wherein said photodiodes comprise photodiodes vapor-deposited on both sides of said glass carrier.

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US005440130A

United States Patent [19]

Cox et al.

[11] Patent Number: 5,440,130

[45] Date of Patent: * Aug. 8, 1995

[54] X-RAY IMAGING SYSTEM AND SOLID STATE DETECTOR THEREFOR

[75] Inventors: John D. Cox; William R. Eisenstadt; Robert M. Fox, all of Gainesville, Fla.

[73] Assignee: General Imaging Corporation, Gainesville, Fla.

[*] Notice: The portion of the term of this patent subsequent to Feb. 27, 2007 has been disclaimed.

[21] Appl. No.: 76,138

[22] Filed: Jun. 14, 1993

Related U.S. Application Data

[63] Continuation of Ser. No. 750,273, Aug. 27, 1991, Pat. No. 5,220,170, which is a continuation-in-part of Ser. No. 462,042, Jan. 8, 1990, Pat. No. 5,043,582, which is a continuation-in-part of Ser. No. 151,235, Feb. 1, 1988, Pat. No. 4,905,265, which is a continuation-in-part of Ser. No. 807,650, Dec. 11, 1985.

[51] Int. Cl.[6] G01T 1/24; G01T 1/16

[52] U.S. Cl. 250/370.09; 378/98.8

[58] Field of Search 250/370.09, 370.11; 378/99, 37, 98.8; 358/111

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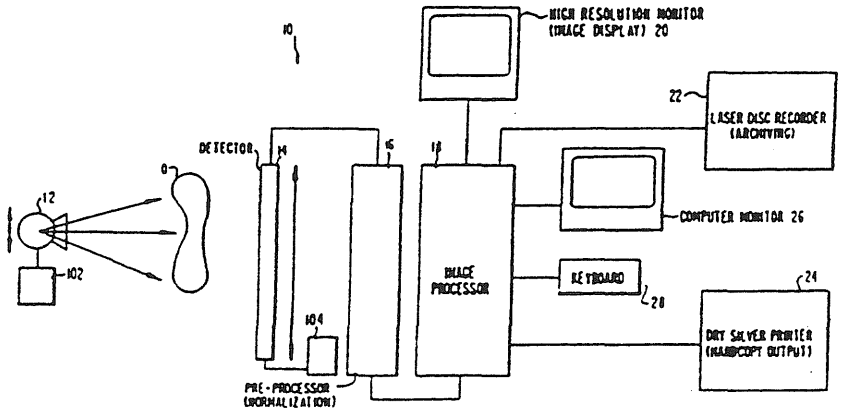
Assistant Examiner—Edward J. Glick
Attorney, Agent, or Firm—Foley & Lardner

[57] ABSTRACT

The x-ray imaging system comprises an x-ray source for producing an x-ray beam having an energy of at least 30 kVp and an x-ray detector. The x-ray detector comprises a solid state integrated circuit having a silicon substrate and a plurality of charge storage devices. The detector is responsive to x-rays of at least 30 keV to directly produce free electrons which interact with the charge storage devices.

4 Claims, 18 Drawing Sheets



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US005521385A

United States Patent [19]

Pandelisev

[11] Patent Number: 5,521,385

[45] Date of Patent: May 28, 1996

[54] **LONG LIFE GAMMA CAMERA PLATE ASSEMBLY WITH IMPROVED REFLECTOR SYSTEM**

[75] Inventor: Kiril A. Pandelisev, Mesa, Ariz.

[73] Assignee: Optoscint, Inc., Mesa, Ariz.

[21] Appl. No.: 203,574

[22] Filed: Mar. 1, 1994

[51] Int. Cl.[6] G01T 1/161

[52] U.S. Cl. 250/363.02; 250/368

[58] Field of Search 250/368, 367, 250/369, 363.02, 363.10

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Primary Examiner—Davis L. Willis

Assistant Examiner—Richard Hanig

Attorney, Agent, or Firm—James Creighton Wray

[57] ABSTRACT

This invention relates to a fabrication of a gamma camera plate assembly that has long life and improved efficiency. Cladding and reflecting layers provide improvements in crystal output. Seals prevent moisture leaks, prolonging lifetime. Multi-barrier epoxy-filled seals and desiccant-filled recesses, elastomer-filled spaces and an extra optical coupling layer provide prolonged life and improved efficiency. Exterior rings with new glass-to-metal seals and metal-to-metal seals provide strong watertight assemblies. The gamma camera plate includes a crystal having an optical cladding and a reflector surrounding the cladding. A glass mounting plate is connected to one flat surface of the crystal by an optical coupler. A mounting ring surrounds the crystal and an outer surface of the glass plate. Barriers are formed in upper and lower surfaces of the mounting ring, and complementary barriers are formed in engaging surfaces of the glass plate and of the gamma ray window plate. Recesses within the barriers hold desiccant. An elastomer fills a space between the central opening in the mounting ring and the crystal, and an optical coupler fills the space between the window and the reflector. Auxiliary rings connect an outer surface of the glass plate through glass-to-metal seals and metal-to-metal seals with the main mounting ring. Thin low heat sink rings form the final metal-to-metal seals to prevent heat transfer to the crystal.

52 Claims, 2 Drawing Sheets

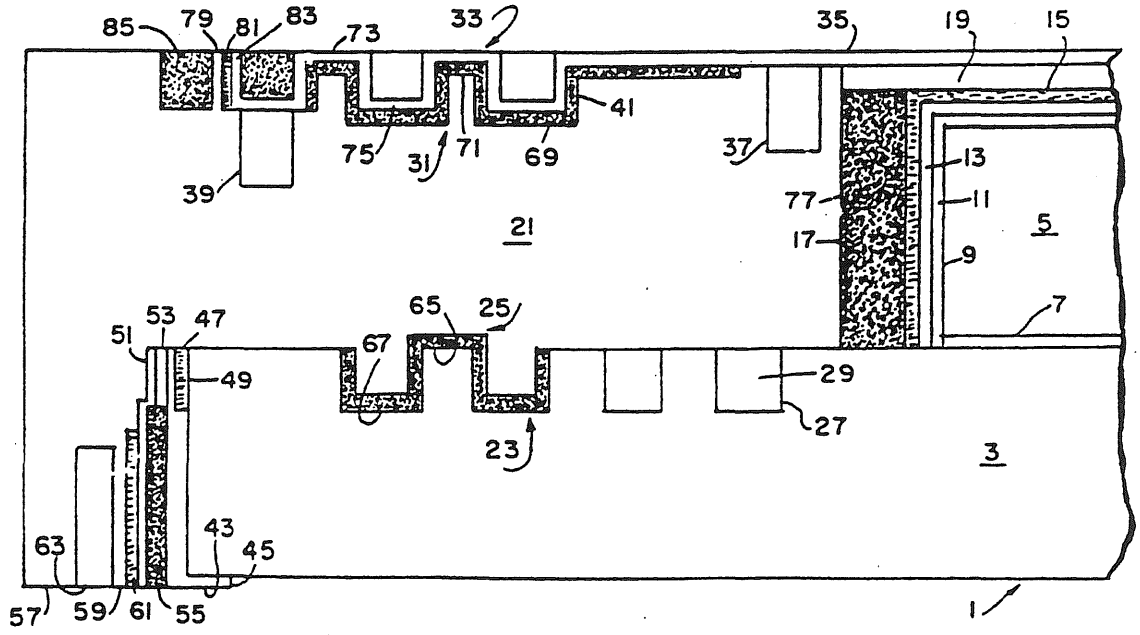
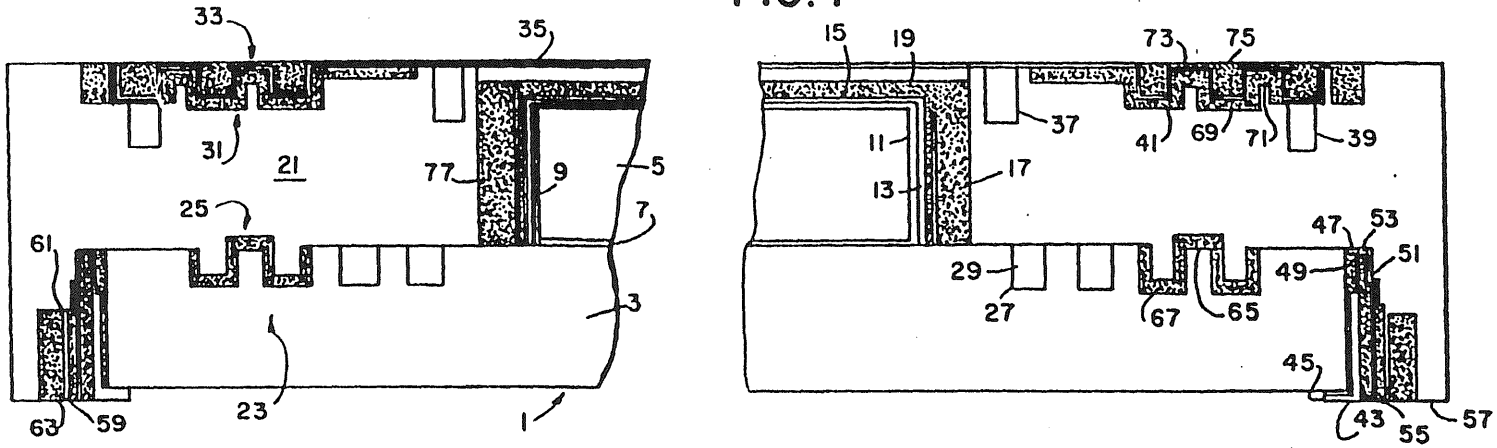


FIG. 1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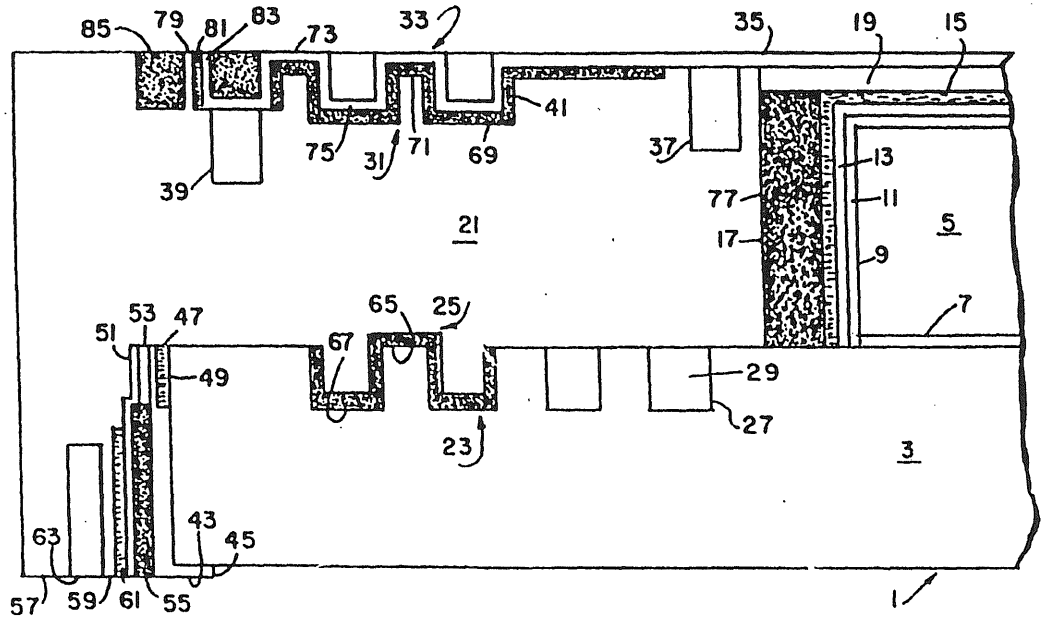
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FIG. 2

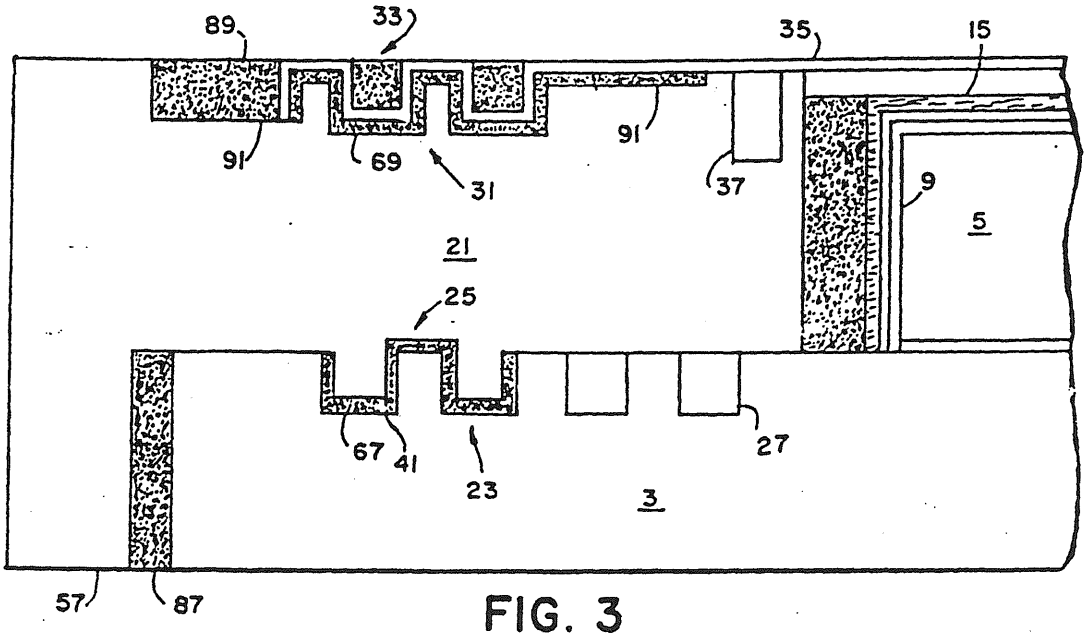
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FIG. 3

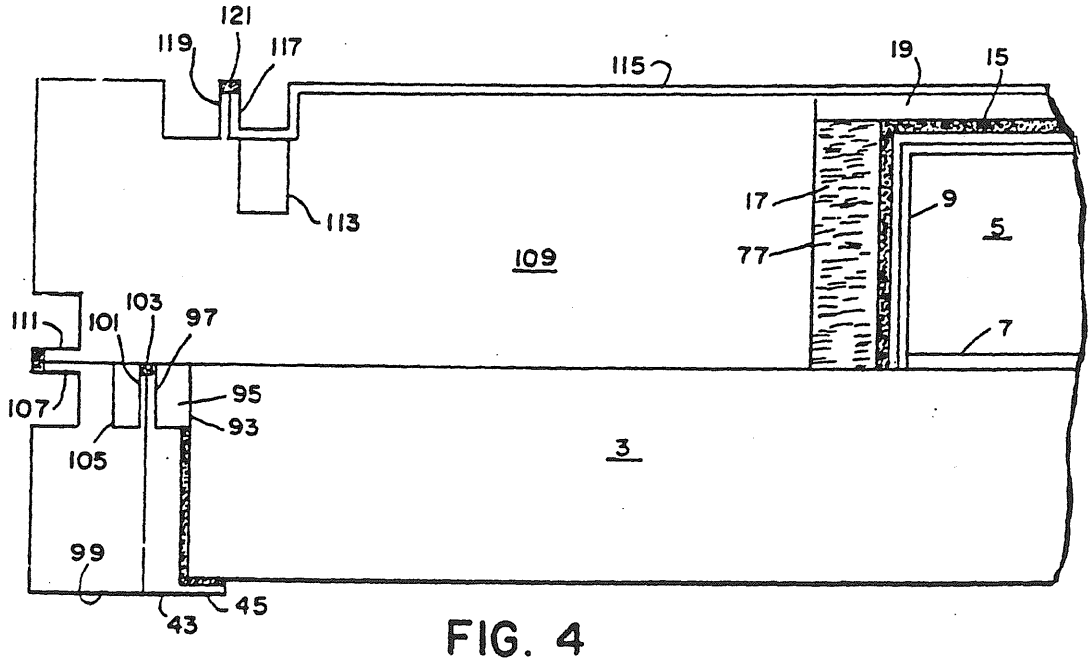
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FIG. 4

LONG LIFE GAMMA CAMERA PLATE ASSEMBLY WITH IMPROVED REFLECTOR SYSTEM

BACKGROUND OF THE INVENTION

The present invention relates to scintillation crystal plate assemblies used in gamma cameras.

Prior art crystal plate assemblies are sealed using epoxies and various resins. Light reflectors used on crystals MgO powder applied on the crystal surfaces by spraying or painting a solution of white oxide powder and organic water-free base.

Crystal plate assemblies prepared using the prior art procedures have short lifetimes. Prior art plate assemblies do not allow optimum efficiency. Available crystal plate assemblies do not permit use of thin glass plates, since crystals are supported only by the glass plates.

Needs have long existed for improved gamma camera plates. Specifically, needs have existed for lighter weight assemblies. Gamma camera plates are needed which will have long life and improved efficiency.

SUMMARY OF THE INVENTION

The current invention provides new special crystal sealing procedures for gamma camera plates that extend their useful lifetimes and allow for reflective systems that increase the efficiency of the gamma camera so as to produce a sharper image of the human organ/body being investigated.

The present invention allows for hermetic sealing of the hygroscopic sodium iodide crystals by multi-barrier seals. The new seals of the invention use (1) epoxy, (2) mixtures of epoxy, glass-to-metal seals and metal-to-metal soldering, and (3) all welded joints and glass-to-metal seals, all with new physical shapes and constructions.

In the new all-epoxy multi-barrier seals, barriers have been introduced to prevent crack propagation in the epoxy, as well as to prevent possible moisture penetrating past those cracks. The crystals are further sealed by cladding layers and reflective coatings. All crystals are encapsulated by cladding layers and optical couplers.

The combination of epoxy, glass-to-metal and metal-to-metal soldering is introduced by this invention to facilitate some mechanical advantages of assembly for sealing sodium iodide (NaI) thallium-doped crystals. This method, as in the all epoxy method, provides hermetic seals for the crystal plates and allows for crystal encapsulation in cladding layers and reflective coatings, and by doing so it allows for increased efficiency of the gamma cameras.

Most rugged and easiest to apply is the welding and glass-to-metal seal approach. This combination produces hermetic seals that provide for long life of the gamma camera plate assemblies. This approach also provides full crystal encapsulation by means of cladding layers and diffusive or metal reflective coating.

All three approaches of this invention lead to long life gamma camera assemblies with improved energy characteristics. The invention eliminates special mountings for the assemblies required by various manufacturers. The invention eliminates the need for the design of special tools used in the gamma camera plate assembly fabrication processes and improves crystal sealing.

The present invention provides unique approaches for extending the life of gamma camera plate assemblies, and increases efficiency through introduction of high quality

reflectors. The invention improves resolving capabilities of gamma cameras. Resolution is in part a function of spacing between a crystal plane and photomultiplier input windows. The invention allows for reducing the glass plate thickness by a factor of four or more.

The multi-barrier seal for this long life, higher efficiency gamma camera plate assembly is made by using only epoxy, or by epoxy, glass-to-metal and metal-to-metal soldering, or by glass-to-metal seals and metal-to-metal welding. All three combinations lead to an improved gamma camera plate assembly. The difference between the approaches is only in the design of various parts of the gamma camera and its assembly process.

The all-epoxy sealed gamma camera plate assembly consists of a mounting ring, a glass plate, a crystal with a multi-layer metal reflector and a thin aluminum gamma ray window.

First the crystal with the reflector is attached to the glass plate with an optical coupler. The glass plate with the crystal is then attached to the metal barrier using epoxy. A multi-barrier seal is used to prevent crack propagation and moisture penetration through the cracks.

Fastening of the crystal to the metal barrier is done in two steps. First the space between the crystal and the metal barrier is filled with a silicone rubber material. In this way the glass plate is relieved of the weight of the crystal, and at the same time serves as a barrier for possible moisture penetration. The part above the elastomer and the multi-layered reflector is filled with optical coupling material stable to the exposure of the gamma rays. The aluminum radiation window is placed on the top using the multi-barrier seal assembly.

The no-epoxy seal gamma camera assembly of this invention consists of three metal rings, a glass plate, crystal with a multi-layer reflector, and an aluminum gamma ray window.

First the glass plate is connected to the first ring with a glass-to-metal seal. For this purpose the glass is doped with lead and the soldering is done with In-Zn alloy having a melting point between 200° C.–300° C.. The ratio of indium vs. zinc determines the exact melting temperature. The metal ring is either stainless steel or aluminum electroplated with Zn.

The glass plate and ring assembly is welded to the second ring surrounding the first metal ring. A seam weld is used for this purpose. After that, using an optical coupler, the crystal with the already deposited reflector is mounted on the glass plate with the two metal ring assemblies.

The third ring is then connected to the second ring by seam welding. After fastening the crystal to the third ring with silicone rubber and optical coupling material, the gamma ray window is welded to the third ring.

All contact surfaces contain moisture barriers consisting of pockets of desiccant.

The epoxy, glass-to-metal seal, metal-to-metal soldering gamma camera plate assembly consists of a glass plate, a crystal with a multi-layer reflector, three metal barriers and an aluminum gamma ray window.

First the glass plate is connected to the first (inner) metal ring by a glass-to-metal seal. Here the ring is Al or stainless steel electroplated with Zn, and the glass surface is doped with Pb or indium and a glass-to-metal seal is formed. The glass plate-inner ring assembly is then soldered to the second (middle) ring using the same In-Zn solder.

After that the crystal with the multi-layer reflector is connected to the glass plate with the optical coupler.

The middle ring is either soldered or welded to the third outer metal ring, and a multiple ring seal is applied between the glass plate and the third ring as an extra measure for ensuring strength and moisture barrier.

The crystal is fastened to the third ring by a silicone rubber and optical coupling layer over the crystal. The aluminum gamma ray window is connected to the top surface of the top ring using either metal-to-metal soldering or seam welding.

All three embodiments of this invention and other combinations provide for fabrication of long life, higher efficiency gamma plate assemblies. The spacial resolution of a gamma camera employing the plate assembly of this invention is improved when the thin glass plate is used.

A gamma camera plate includes a crystal having an optical cladding and a reflector surrounding the cladding. A glass mounting plate is connected to one flat surface of the crystal by an optical coupler. A mounting ring surrounds the crystal and an outer surface of the glass plate. Barriers are formed in upper and lower surfaces of the mounting ring, and complementary barriers are formed in engaging surfaces of the glass plate and of the gamma ray window plate. Recesses within the barriers hold desiccant. An elastomer fills a space between the central opening in the mounting ring and the crystal, and an optical coupler fills the space between the window and the reflector. Auxiliary rings connect an outer surface of the glass plate through glass-to-metal seals and metal-to-metal seals with the main mounting ring. Thin low heat sink rings form the final metal-to-metal seals to prevent sealing heat transfer to the crystal.

These and further and other objects and features of the invention are apparent in the disclosure, which includes the above and ongoing written specification, with the claims and the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a cross-sectional view of a gamma camera plate showing a crystal, a glass mounting plate, a sealing ring and combination seals showing the multiple barriers and epoxy seals, glass-to-metal seals and metal-to-metal seals.

FIG. 2 is an enlarged cross-sectional detail of the structure shown in FIG. 1.

FIG. 3 is an enlarged cross-sectional detail of an edge of a crystal and mounting plate assembly showing a crystal, a glass mounting plate, a mounting ring and epoxy disposed in multi-barrier seals.

FIG. 4 is a cross-sectional detail of a gamma camera mounting plate assembly showing one preferred embodiment having a crystal or glass plate, multiple cladding layers, a reflective layer and multiple mounting rings which are sealed with a glass-to-metal seal and metal welds.

DETAILED DESCRIPTION OF THE DRAWINGS

Referring to FIGS. 1 and 2, a gamma camera plate assembly is generally indicated by the numeral 1. The gamma camera plate assembly has a large glass mounting plate 3 and a crystal 5 joined to the mounting plate by an optical coupler 7. The crystal is surrounded by cladding 9, which is made up of first and second layers 11 and 13 respectively. The cladding is surrounded by a reflective layer 15. The reflective layer 15 is surrounded by an elastomeric layer 17, and the elastomeric layer 17 is overlaid by an optical coupler layer 19. A large metal ring 21 surrounds the outer surface of the crystal and the outer surface of the mounting plate.

Barriers 23 in the mounting plate cooperate with complementary barriers 25 in the mounting ring, and recesses 27 in the glass mounting plate hold desiccant 29. Similar complementary barriers 31 are formed in the mounting plate to inter-engage complementary barriers 33 in the gamma ray window 35.

Recess 37 in the mounting ring 21 receives desiccant 29. Recess 39 also receives desiccant to prevent ingress of moisture beyond the barriers.

Epoxy 41 is disposed in the inter-engaging barriers.

A first metal ring 43 surrounds an outer end of the glass plate 3. A lower inward projecting lip 45 on the first metal ring 43 underlies an outer lower surface portion of the plate 3. Metal ring 43 is joined to an outer surface of the glass plate by a glass-to-metal seal 47. Preferably the surface of the glass plate 3, which is adjacent the glass-to-metal seal 47, is doped with a metal which is compatible to a metal in the alloy, which preferably forms the glass-to-metal seal 47.

The dopant may be lead or indium and the alloy, for example, may be a zinc indium alloy, which has a melting point between about 200° C. and 400° C., depending on the composition.

The first metal ring 43 may be a zinc-plated aluminum or stainless steel ring.

A second metal ring 51 is joined to the first metal ring by a metal-to-metal seal 53 which may be an appropriate alloy, such as an indium-zinc alloy, with an appropriate melting point, such as from about 200° C. to about 400° C.

The metal-to-metal seals are made at the top of the ring, and wide space at the bottom of the ring is filled with an elastomer 55.

The mounting ring 21 is formed with an extended outer surface 57, which serves as a mechanical protection for the outer seals and as a locus for coupling to the main gamma camera assembly.

A thin metal ring 59 is formed in the mounting ring 21, and the thin metal ring 59 is joined to the second metal ring 51 by a metal-to-metal seal 61, or by welding. The gap 63 between the thin integral metal ring 59 and the outer extension 57 is filled with an elastomer.

The first, second and third rings allow the first and second rings to be joined by alloys before the introduction of the crystal. The space 55 between the first and second rings provides heat isolation from the glass plate when the ring 59 is joined to the ring 51 by alloy soldering or welding. Elastomer is added to the spaces 55 and 63 after all of the rings are joined.

Before assembly, the glass plate 3 has been formed with the barriers 23, which include projections 65 and recesses 67, and with the desiccant-receiving recesses 27. The sealing ring 21 has been formed with the barriers 31, which include the recesses 69 and the projections 71, and with the desiccant-receiving recesses 37 and 39. The thin gamma window plate 35 is formed with the barriers 33, which include recesses 73 and projections 75. The crystal has been coated with the cladding 9 and the reflector 15. The cladding layers preferably have an index of refraction of about 1.5, with the refraction of the inner layer being slightly greater than the index of refraction of the outer layer. An optical coupler could be an acrylic having an index of refraction of about 1.42 to 1.48, and the glass mounting plate may have an index of refraction of about 1.5 to 1.6.

In the mounting procedure, the first ring 43 is attached to the surrounding outer surface of the plate, and then the second ring 51 is attached to the first ring.

Then the optical coupler 7 is spread as a liquid on the lower surface of the crystal 5 and on the center of the upper surface of the glass plate 3. The crystal 5 with its cladding and reflecting coating is placed with one edge of the crystal and optical coupler contacting the glass plate. Then the crystal is rotated into full contact with the glass plate, pressing the crystal as the crystal is lowered to ensure the escape of any gases so that the optical coupler is clear.

Epoxy 41 is placed in the recesses 67, desiccant 29 is placed within the recesses 27, and the mounting ring 21 is placed on top of the glass plate 3 and is pressed into place. Then the outer ring 59 is joined to the second ring 51, anchoring the plate 21 on the mounting plate 3. Then the recesses 55 and 63 are filled with an elastomer.

Elastomer 17 is added to fill the space between the opening 77 in the ring 21 and the reflective layer 15 which surrounds the crystal, and finally an optical coupler 19 is added on top of the reflective layer 15 and on upper edges of the resilient layer 17 to seal the reflective layer and edges of the resilient layer 17 to the inner surface of the gamma ray window plate 35.

In the next step, resin 41 is deposited in the recesses 69 and desiccant is deposited in the recesses 37 and 39 in the sealing ring and the gamma ray window plate 35, which is a thin aluminum sheet. The barrier seals 33 are pressed down into the epoxy. Then the thin ring 79 of the mounting ring 21 is joined by a metal-to-metal seal 81 to the outer surface 83 of the gamma ray window plate 35. Finally, the recess 85 is filled with an elastomer.

By forming the glass-to-metal and the metal-to-metal seals between the glass mounting plate 3 and the first and second rings and the metal-to-metal seals between the second and third metal rings before the crystal is joined to the glass mounting plate, the crystal is protected from increased temperatures. Moisture is prevented from entering the crystal by the metal-to-metal seals and the glass-to-metal seals and by the epoxy-filled barrier seals, and finally by desiccant in the desiccant-containing recesses.

The epoxy-filled barrier seals, because of the serpentine shape of the epoxy which conforms to the shape of the structure, prevent any crack in the epoxy from propagating completely inward within the epoxy, and therefore prevent transfer of moisture through epoxy cracks.

An epoxy multiple barrier seal is shown in FIG. 3. Similar elements have similar numbers. In this case, the metal rings at the outer surface of the glass plate 3 are replaced by an epoxy seal 87. The metal-to-metal seal at the outer edge of the gamma ray window plate 35 is replaced by an epoxy seal 89. Since epoxy 91 shows the entire recesses 69, the outer desiccant-holding recess 39 shown in FIG. 1 is eliminated from FIG. 3.

In the assembly procedure for FIG. 3, the barriers 23 and recesses 27 are preformed in the glass plate 3, and the barriers 25 and 31 and recess 37 are preformed in the mounting ring 21. The barriers 33 are preformed in the gamma ray window plate 35. The cladding 9 and reflecting layer 15 are preformed on the crystal 5.

In the first assembly step, the optical coupler is spread on the lower surface of the crystal 5 and on the upper surface of the mounting plate 3, and the crystal is placed on the mounting plate by first placing an edge of the crystal on the glass plate 3, and then rocking the crystal downward so that the optical coupling is joined in a moving line, which ensures against the entrapment of gas. After the crystal 5 is mounted on the plate 3, the mounting ring 21 is added with the crystal received in central opening 7 and the extension 57 extending downward around the outer surface of the glass plate 3. Epoxy 41 is added to the recesses 67 and desiccant is placed in the recesses 27. Then the epoxy 87 is filled in the space between the downward extension 57 and the outer surface of the glass plate 3. Then the elastomer 17 is added to the space to fill the gap between the opening 17 and the reflective layer 15.

The optical coupler 19 is added atop the reflective layer 15. Epoxy 41 and 91 fills the recesses 69 in the upper surfaces of the mounting plate 21, and desiccant is placed in the recess 37. Then the gamma ray window plate 35 is put in place, and the barriers 33 are pressed down into the epoxy 41. Finally, epoxy 89 is added and the system is ready for use. The barriers prevent continuous cracks of the epoxy which might admit moisture inward by preventing crack propagation. The desiccant traps any moisture molecules which might move inward, and prevents them from entering the surfaces within the reflector and cladding.

In FIG. 4, the preferred form of the invention uses multiple low continuous seam welds on low heat sink seams.

A metal ring 43 with an inward projecting lower lip 45 is connected to an outer surface 93 of the glass plate with a glass-to-metal seal, which is preferably an alloy which bonds to a restricted doped area of the glass. The metal ring 43 has a continuous thin upward projection 97. A second metal ring 99 with a complementary thin upward projection 101 is positioned adjacent the first metal ring, and the first and second metal rings are joined by a seam weld 103 or by soldering with an alloy. The rings are joined together by an alloy solder. It is preferable to first electroplate the surfaces to be soldered with a metal such as zinc.

The second ring has a recess 105 adjacent the upper projection 101, and has an outer projection 107.

The crystal 5 is secured on the plate 3, as previously described. Then desiccant is added to the recesses 95 and 105. Large ring 109 is placed atop the glass plate 3. A projection 111, which is complementary to projection 107 on the second ring, is welded or soldered, as previously described. The projections 97, 101, 107 and 111 prevent or reduce heat contact through the glass plate or through the major ring 109 toward the crystal. The plate 109 is preformed with a recess 113 for receiving desiccant.

An elastomer 17 fills the space between the opening 77 and the reflective layer 15, and optical coupling material 19 is added to the top of the reflective layer 15 and the top of the elastomeric coating 17 within the opening 77. Desiccant is placed within recess 113, and a gamma ray window plate 115 with a preformed projection 117 is placed on the top of the optical coupler 19 and ring 109. The ring 109 is formed with an upward facing projection 119, which is complementary to the end surface 121 of the gamma ray window plate 115, and the seam at the tips of the projections 121 and 119 is sealed by welding or soldering, as previously describing, completing the construction of a gamma plate.

While the invention has been described with reference to specific embodiments, modifications and variations of the invention may be constructed without departing from the scope of the invention, which is defined in the following claims.

I claim:

1. A gamma camera plate, comprising a large flat crystal, an optical coupler on the crystal and a large glass plate connected to the optical coupler and having a ledge extending outward beyond the crystal, a cladding surrounding a remainder of the crystal, a reflective layer surrounding the cladding, an elastomer surrounding the reflective layer, an

optical coupling overlying the reflective layer, a metal plate overlying the optical coupling and the elastomer and having an extension extending outward beyond the elastomer, a main mounting ring extending around the elastomer and positioned between the metal plate extension and the glass plate ledge, a first set of complementary multiple inter-engaging barriers formed in the glass plate ledge and in the ring, epoxy disposed in the first inter-engaging barriers, a second set of complementary multiple inter-engaging barriers formed in the metal plate extension and in the ring, and epoxy disposed in the second inter-engaging barriers, a first inner recess between the glass plate ledge and the ring and desiccant disposed in the first recess, and a second recess in the ring adjacent the metal plate extension and desiccant disposed in the second recess.

2. The apparatus of claim 1, wherein the cladding comprises a first cladding layer adjacent the crystal and a second cladding layer surrounding the first cladding layer.

3. The apparatus of claim 2, wherein the first and second cladding layers have different indexes of refraction.

4. The apparatus of claim 1, wherein the reflective layer is a metal reflecting layer.

5. The apparatus of claim 4, wherein the reflecting layer is made of metal sputtered, evaporated or deposited on a metal foil.

6. The apparatus of claim 4, wherein the metal reflecting layer is made of gold, silver or aluminum.

7. The apparatus of claim 1, wherein the reflective layer is a diffuse white reflective layer having finely divided reflective powder held in a resin.

8. The apparatus of claim 1, further comprising a glass-to-metal seal between the glass plate and the ring and surrounding the crystal, the glass-to-metal seal further comprising a metal alloy and a metal doped section of the glass plate immediately adjacent the metal alloy.

9. The apparatus of claim 1, wherein the glass plate is thinner than the crystal.

10. The apparatus of claim 1, wherein the glass plate is about one third or less as thick as the crystal.

11. The apparatus of claim 1, wherein the main mounting ring extends around an outer edge of the glass plate, and further comprising a zinc plated aluminum or stainless steel second ring surrounding the outer surface of the glass plate, a glass-to-metal seal between the outer surface of the glass plate and the second ring, a third ring surrounding the second ring, a metal-to-metal seal joining the third ring to the second ring, and a second metal-to-metal seal joining the third ring to the main mounting ring.

12. The apparatus of claim 11, further comprising a thin metal extension on the main mounting ring adjacent the second ring, and wherein the second metal-to-metal seal surrounds an outer surface of the second metal ring and joins the thin metal extension to the second ring, and an elastomer in a recess surrounding the second metal-to-metal seal.

13. The apparatus of claim 12, further comprising an outer desiccant recess in the main ring adjacent an outer portion of the metal plate extension, and desiccant disposed in the outer desiccant recess.

14. A gamma camera plate comprising a flat crystal, an optical coupler on one large flat surface of the crystal, a glass plate connected to the optical coupler, the glass plate having a lateral extension beyond the crystal, a metal ring surrounding the crystal and having a portion laterally extended from the crystal which lies adjacent the lateral extension of the glass plate, a portion of the lateral extension of the glass plate surrounding the crystal being doped prior to sealing with a metal dopant, a metal alloy seal engaging the doped portion of the glass plate and the metal housing.

15. The apparatus of claim 14, further comprising a cladding surrounding a remainder of the crystal which is not contacted by the optical coupler, and a reflective layer overlying the cladding.

16. The apparatus of claim 15, wherein the cladding comprises a first cladding layer in contact with the crystal and a second cladding layer in contact with the first cladding layer, the first and second cladding layers having different indexes of refraction.

17. The apparatus of claim 15, further comprising an elastomer surrounding the reflective layer.

18. The apparatus of claim 14, further comprising complementary inter-engaging barriers in the extended glass adjacent the housing extension, and epoxy positioned in the barriers for providing a long life hermetic seal between the glass plate and extension and the housing extension, whereby the inter-engaging barriers provide an epoxy cracked propagation barrier.

19. The apparatus of claim 18, further comprising recess barriers between the inter-engaging barriers and the crystal for receiving silica gel and preventing moisture ingress.

20. A gamma camera plate, comprising a large flat crystal, an optical coupler on the crystal and a large glass plate connected to the optical coupler and extending outward beyond the crystal, a cladding surrounding a front and a back of the crystal, and a reflective layer surrounding the cladding.

21. A gamma camera plate, comprising a large flat crystal having a front and a back, an optical coupler on the crystal and a large glass plate connected to the optical coupler and extending outward beyond the crystal, a mounting plate surrounding the crystal and overlying the glass plate, elastomeric material surrounding the crystal within an opening in the mounting plate, a gamma ray window plate overlying the back of the crystal, and an optical coupler between the window plate and the back of the crystal.

22. A gamma camera plate, comprising a large flat crystal, an optical coupler on the crystal and a large glass plate connected to the optical coupler and extending outward beyond the crystal, a mounting plate surrounding the crystal and overlying the glass plate, a gamma ray window plate overlying the crystal and mounting plate, and multiple barriers comprising complementary mutually inter-engaging projections and grooves in the glass plate and mounting plate, and in the window plate and mounting plate, and epoxy disposed in the multiple barriers.

23. The apparatus of claim 22, further comprising a first metal ring surrounding outer surfaces of the glass plate, and a glass-to-metal seal connecting the first ring to the outer surface of the glass plate.

24. The apparatus of claim 23, further comprising a second ring surrounding the first ring, and a metal-to-metal seal between the first and second ring.

25. The apparatus of claim 24, wherein the second ring has a thin surface, and wherein the mounting plate has a thin projection, and further comprising a metal-to-metal seal between the thin surface and thin projection.

26. The apparatus of claim 25, wherein the metal-to-metal seal is a seam seal formed by welding or by electroplating and alloy soldering.

27. The method of constructing a gamma camera plate, comprising forming a glass plate with multi-barrier projections and grooves around a locus of a crystal, forming a mounting plate with complementary multiple projections and grooves, coating a large flat surface of a crystal with an optical coupler and coating an area on the glass plate with an optical coupler, contacting an optical coupler-coated edge of

the crystal with a coated area on the glass plate, rocking the crystal into full contact with the optical coupling on the glass plate, thereby forming an optical coupling between the crystal and the glass plate without voids or bubbles, placing epoxy in grooves on one of the plates, placing the mounting plate on the glass plate and around the crystal, and pressing the inter-engaging multiple barriers together and filling the spaces between the barriers with epoxy.

28. The method of claim 27, further comprising the initial step of joining a first metal ring to an outer edge of the glass plate with a glass-to-metal seal, and joining a second outer ring to the first ring with a metal-to-metal seal before joining the mounting plate to the glass plate.

29. The method of constructing a gamma camera plate, comprising joining a first metal ring to an outer edge of a glass plate with a glass-to-metal seal, and joining a second outer ring to the first ring with a metal-to-metal seal, coating a large flat surface of a crystal with an optical coupler and coating an area on the glass plate with an optical coupler, contacting an optical coupler-coated crystal with a coated area on a glass plate, pressing the crystal into full contact with the optical coupling on the glass plate, thereby forming an optical coupling between the crystal and the glass plate without voids or bubbles, placing a mounting plate on the glass plate and around the crystal, and joining the mounting plate to the glass plate by joining a thin extension on the second outer ring and a thin extension on the mounting plate with a metal-to-metal seal.

30. A crystal mounting having glass-to-metal seal comprising a glass plate, a metal plate adjacent the glass plate, an area of the glass plate adjacent the metal plate being doped with a metal dopant prior to sealing and an alloy compatible with the dopant contacting and sealing the metal doped area of the glass plate and the metal plate and joining the glass plate and metal plate in a glass-to-metal seal.

31. A gamma camera plate assembly comprising a crystal, an optical coupler on the crystal, a glass plate connected to the optical coupler and extending outward beyond the crystal, a window plate overlying the crystal and having an extension extending outward beyond the crystal, a main mounting plate extending beyond the crystal and the glass plate, a first metal ring surrounding an outer surface of the glass plate, a glass-to-metal seal joining the first ring to the glass plate, the first ring having a first thin extension, a second metal ring adjacent the first ring and having a second thin extension, a first metal-to-metal seal joining the first and second thin extensions and joining the first and second metal rings, the second ring having a third thin extension and the mounting plate having a fourth thin extension, a second metal-to-metal seal joining the third and fourth extensions and joining the second ring and the mounting plate.

32. Apparatus comprising a crystal, an optical coupler on the crystal and a glass plate connected to the optical coupler and having a ledge extending outward beyond the crystal, a cladding surrounding a remainder of the crystal, a reflective layer surrounding the cladding, an elastomer overlying the reflective layer, a plate overlying and having an extension extending outward, a main mounting ring extending around the crystal and positioned between the extension and the ledge, a first set of complementary multiple inter-engaging barriers formed in the ledge and in the ring, epoxy disposed in the first inter-engaging barriers, a first inner recess between the ledge and the ring and desiccant disposed in the first recess.

33. The apparatus of claim 32, further comprising a second set of complementary multiple inter-engaging barriers formed in the extension and in the ring, and epoxy disposed in the second inter-engaging barriers, and a second recess in the ring adjacent the metal plate extension and desiccant disposed in the second recess.

34. The apparatus of claim 32, further comprising a glass-to-metal seal between the glass plate and the ring and surrounding the crystal, the glass-to-metal seal further comprising a metal alloy and a metal doped section of the glass plate immediately adjacent the metal alloy.

35. The apparatus of claim 32, wherein the main mounting ring extends around an outer edge of the glass plate, and further comprising a zinc plated aluminum or stainless steel second ring surrounding the outer surface of the glass plate, a glass-to-metal seal between the outer surface of the glass plate and the second ring, a third ring surrounding the second ring, a metal-to-metal seal joining the third ring to the second ring, and a second metal-to-metal seal joining the third ring to the main mounting ring.

36. The apparatus of claim 35, further comprising a thin metal extension on the main mounting ring adjacent the second ring, and wherein the second metal-to-metal seal surrounds an outer surface of the second metal ring and joins the thin metal extension to the second ring, and an elastomer in a recess surrounding the second metal-to-metal seal.

37. The apparatus of claim 36, further comprising an outer desiccant recess in the main ring adjacent an outer portion of the metal plate extension, and desiccant disposed in the outer desiccant recess.

38. Apparatus comprising a crystal, an optical coupler on one surface of the crystal, a glass plate connected to the optical coupler, the glass plate having a lateral extension beyond the crystal, a metal ring surrounding the crystal and having a portion laterally extended from the crystal which lies adjacent the lateral extension of the glass plate, a portion of the lateral extension of the glass plate surrounding the crystal being doped with a metal dopant prior to sealing, a metal alloy seal engaging the doped portion of the glass plate and the metal housing.

39. The apparatus of claim 38, further comprising complementary inter-engaging barriers in the extended glass adjacent the housing extension, and epoxy positioned in the barriers for providing a long life hermetic seal between the glass plate and extension and the housing extension, whereby the inter-engaging barriers provide an epoxy crack propagation barrier.

40. The apparatus of claim 39, further comprising recess barriers between the inter-engaging barriers and the crystal for receiving silica gel and preventing moisture ingress.

41. Apparatus comprising a crystal, an optical coupler on the crystal and a glass plate connected to the optical coupler and extending outward beyond the crystal, a cladding surrounding a remainder of the crystal, a reflective layer surrounding the cladding, an elastomer surrounding the reflective layer, a gamma ray plate overlying the elastomer and extending outward beyond the elastomer, a metal ring extending around the elastomer between the extended gamma ray plate and the extended glass plate, a first set of multiple complementary inter-engaging barriers formed between the glass plate and the ring, and epoxy disposed in the first inter-engaging barriers, a second set of complementary inter-engaging barriers formed in the extended gamma ray plate and in the ring, and epoxy disposed between the inter-engaging barriers, a first recess between the glass plate extension and the ring and desiccant disposed in the recess, and a second recess in the ring adjacent the extended plate and desiccant disposed in the second set of recesses.

42. Apparatus comprising a crystal having a back and a front, an optical coupler on the crystal and a glass plate

connected to the optical coupler and extending outward beyond the crystal, a mounting surrounding the crystal and overlying the glass plate, elastomeric material surrounding the crystal within an opening in the mounting, a gamma ray window overlying the back of the crystal, and an optical coupler between the window plate and the back of the crystal.

43. Apparatus comprising a crystal, an optical coupler on the crystal and a glass plate connected to the optical coupler and extending outward beyond the crystal, a mounting surrounding the crystal and overlying the glass plate, a gamma ray window overlying the crystal and mounting, and multiple barriers comprising complementary mutually inter-engaging projections and grooves in the glass plate and mounting plate, and in the window and mounting plate, and epoxy disposed in the multiple barriers.

44. The apparatus of claim 43, further comprising a first metal ring surrounding outer surfaces of the glass plate, and a glass-to-metal seal connecting the first ring to the outer surface of the glass plate.

45. The apparatus of claim 44, further comprising a second ring surrounding the first ring, and a metal-to-metal seal between the first and second ring.

46. The apparatus of claim 45, wherein the second ring has a thin surface, and wherein the mounting has a thin projection, and further comprising a metal-to-metal seal between the thin surface and thin projection.

47. The apparatus of claim 46, wherein the metal-to-metal seal is a seam seal formed by welding or by electroplating and alloy soldering.

48. The method of constructing a detector, comprising forming a glass plate with multi-barrier projections and grooves around a locus of a crystal, forming a mounting plate with complementary multiple projections and grooves, coating a surface of a crystal with an optical coupler and coating an area on the glass plate with an optical coupler, contacting an edge of the optical coupler-coated surface of the crystal with a coated area on the glass plate, rocking the crystal into full contact with the optical coupling on the glass plate, thereby forming an optical coupling between the crystal and the glass plate without voids or bubbles, placing epoxy in grooves on one of the plates, placing the mounting plate on the glass plate and around the crystal, and pressing the inter-engaging multiple barriers together and filling the spaces between the barriers with epoxy.

49. The method of claim 48, further comprising the initial step of joining a first metal ring to an outer edge of the glass plate with a glass-to-metal seal, and joining a second outer ring to the first ring with a metal-to-metal seal before joining the mounting plate to the glass plate.

50. The method of constructing a detector, comprising joining a first metal ring to an outer edge of a glass plate with a glass-to-metal seal, and joining a second outer ring to the first ring with a metal-to-metal seal, coating a surface of a crystal with an optical coupler and coating an area on the glass plate with an optical coupler, contacting an optical coupler-coated crystal with a coated area on a glass plate, pressing the crystal into full contact with the optical coupling on the glass plate, thereby forming an optical coupling between the crystal and the glass plate without voids or bubbles, placing a mounting on the glass plate and around the crystal, and joining the mounting to the glass plate by joining a thin extension on the second outer ring and a thin extension on the mounting with a metal-to-metal seal.

51. An assembly comprising a crystal, an optical coupler on the crystal, a glass plate connected to the optical coupler and extending outward beyond the crystal, a window plate overlying the crystal and having an extension extending outward beyond the crystal, a main mounting plate extending beyond the crystal and the glass plate, a first metal ring surrounding an outer surface of the glass plate, a glass-to-metal seal joining the first ring to the glass plate, the first ring having a first thin extension, a second metal ring adjacent the first ring and having a second thin extension, a first metal-to-metal seal joining the first and second thin extensions and joining the first and second metal rings, the second ring having a third thin extension and the mounting having a fourth thin extension, a second metal-to-metal seal joining the third and fourth extensions and joining the second ring and the mounting.

52. The apparatus of claim 32, wherein the optical coupling is an elastomer with an appropriate index of refraction.

* * * * *

US005521386A

United States Patent [19]

Taboada

[11] Patent Number: 5,521,386

[45] Date of Patent: May 28, 1996

[54] GAMMA RAY CAMERA METHOD AND APPARATUS

[75] Inventor: John Taboada, San Antonio, Tex.

[73] Assignee: The United States of America as represented by the Secretary of the Air Force, Washington, D.C.

[21] Appl. No.: 387,002

[22] Filed: Feb. 9, 1995

[51] Int. Cl.[6] G01T 1/161; G01T 1/20

[52] U.S. Cl. ..... 250/363.02; 250/368; 250/214 VT

[58] Field of Search ..... 250/363.02, 368, 250/214 VT, 363.10, 370.11

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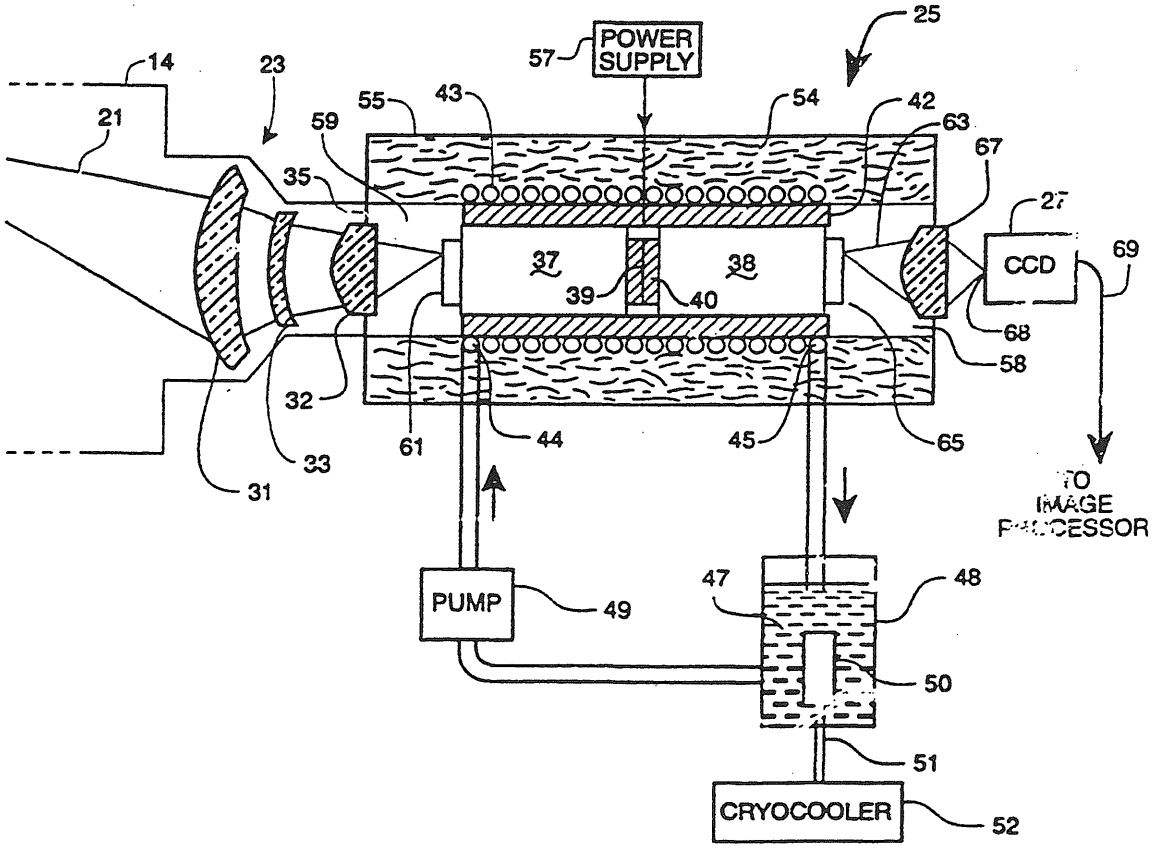
Primary Examiner—Carolyn E. Fields
Assistant Examiner—Edward J. Glick
Attorney, Agent, or Firm—Bobby D. Scearce; Thomas L. Kundert

[57] ABSTRACT

A gamma ray imaging camera system and method for using it are described which in representative embodiments include a gamma ray collimator, a scintillator adjacent the collimator for converting gamma photons into visible photons, a low level visible photon detector including at least two optically coupled inverter tubes, a high-speed lens for imaging the visible photons onto the detector, a video imager for receiving, recording and storing sequential images of the visible photons defining the detector output, and a programmed computer for processing the images and determining the spatial distribution of the images.

16 Claims, 2 Drawing Sheets



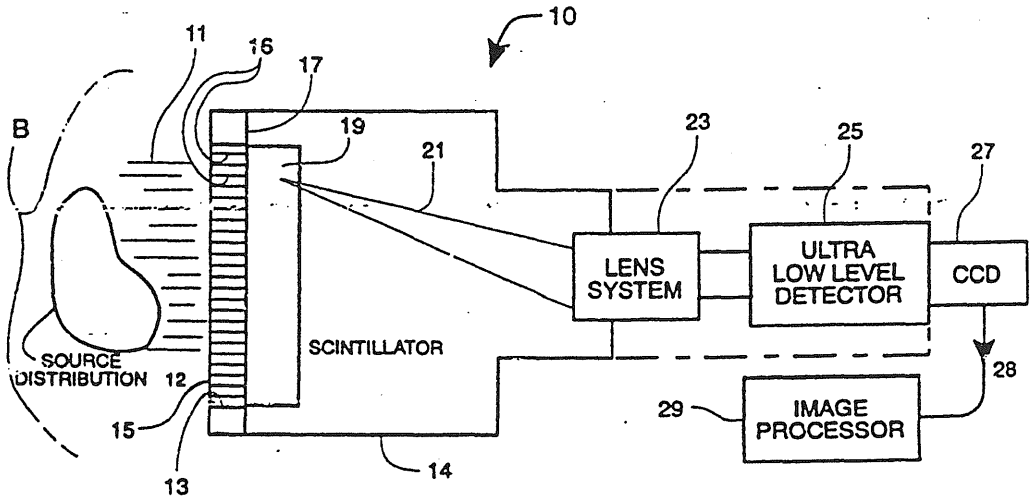
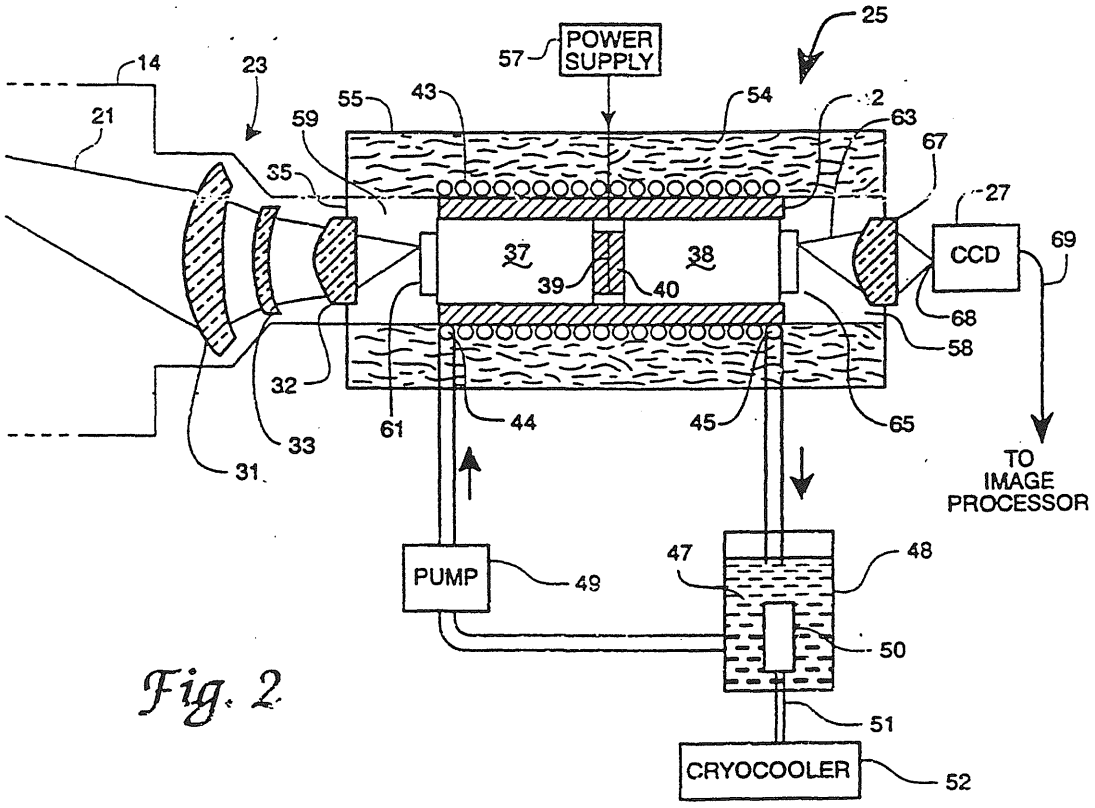

10
11
16
17
B
19
21
23
25
27
LENS SYSTEM
ULTRA LOW LEVEL DETECTOR
CCD
SCINTILLATOR
SOURCE DISTRIBUTION
12
28
29
IMAGE PROCESSOR
15
13
14

Fig. 1


25
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POWER SUPPLY
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40
68
58
32
61
44
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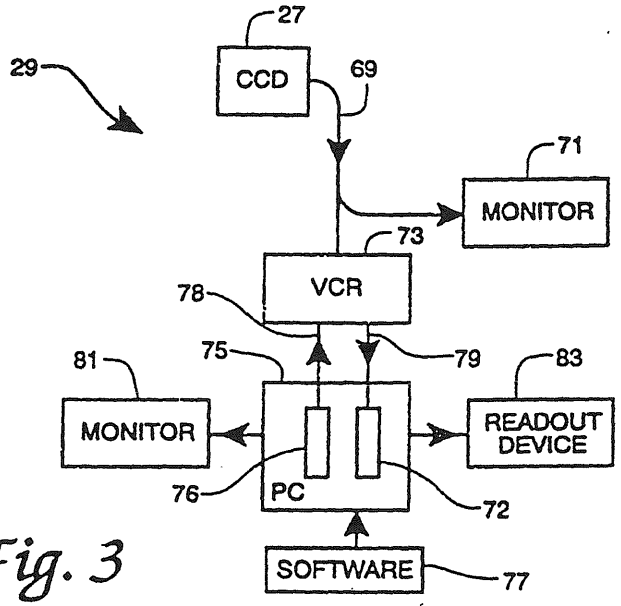
TO IMAGE PROCESSOR
PUMP
49
47
48
50
51
CRYOCOOLER
52

Fig. 2


27
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CCD
69
71
MONITOR
73
VCR
78
79
75
81
83
MONITOR
READOUT DEVICE
76
PC
72
SOFTWARE
77

Fig. 3

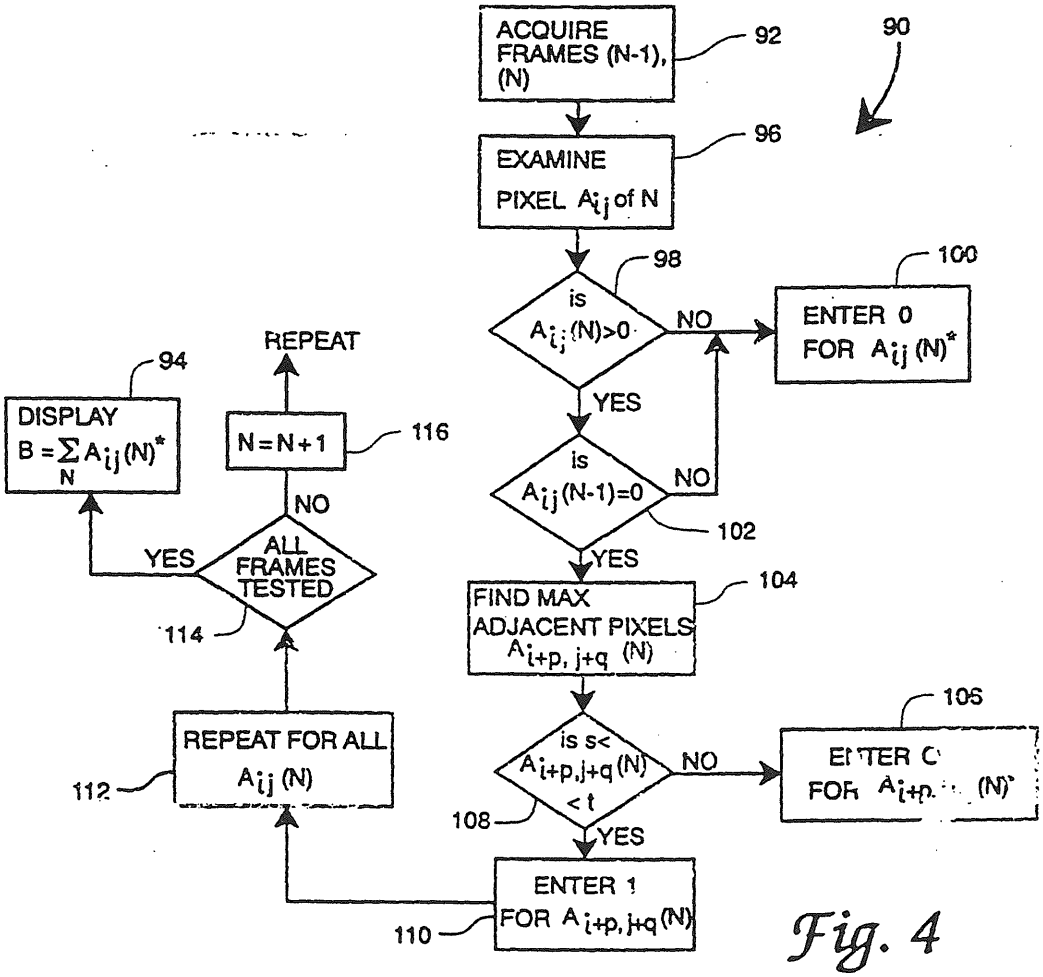
ACQUIRE FRAMES (N-1), (N)
92
90
EXAMINE PIXEL A_{ij} of N
96
98
is $A_{ij}(N)>0$
NO
100
ENTER 0 FOR $A_{ij}(N)^*$
YES
is $A_{ij}(N-1)=0$
NO
102
YES
FIND MAX ADJACENT PIXELS $A_{i+p,j+q}(N)$
104
is s< $A_{i+p,j+q}(N)$ < t
NO
106
ENTER C FOR $A_{i+p...}(N)^*$
108
YES
ENTER 1 FOR $A_{i+p,j+q}(N)$
110
REPEAT FOR ALL $A_{ij}(N)$
112
ALL FRAMES TESTED
114
YES
NO
N=N+1
116
REPEAT
DISPLAY $B=\sum_N A_{ij}(N)^*$
94

Fig. 4

GAMMA RAY CAMERA METHOD AND APPARATUS

RIGHTS OF THE GOVERNMENT

The invention described herein may be manufactured and used by or for the Government of the United States for all governmental purposes without the payment of any royalty.

BACKGROUND OF THE INVENTION

The present invention relates generally to gamma ray imaging detectors and more particularly to a gamma ray camera having application in the field of nuclear medicine for providing spatial images of radioactive substances administered into the body to elucidate internal organ functions.

In nuclear medicine practice, gamma emitting radioisotope containing substances may be introduced into an area of the body under examination, such as the thyroid, and may be localized preferentially into a well defined distribution depending on the chemical and biological activity of the substance. Gamma rays are emitted isotropically from the substance at energies characteristic of the isotope. For example, technicium (99 m) generates gamma rays at about 140 Key and, because of its relatively short half-life (<1 day), is used in many nuclear medicine applications. Because radiation from the substance is isotropic, the gamma rays must be collimated in order to obtain an image of the region of the body into which the radioisotope is introduced.

Detecting gamma ray photons in general requires a high gain process to convert a single photon impact into many free electrons that in turn register an electrical impulse in a counter. For this purpose, Anger (U.S. Pat. Nos. 2,776,377; 2,779,876) used scintillation properties of certain crystals and the high gain provided by photomultiplier tubes; the collimator is coupled to a scintillator crystal through a light tight thin barrier that passes gamma photons but blocks visible photons. The scintillation crystal (typically sodium iodide (NaI)) converts a gamma photon (having energies generally greater than about 40 KeV) into a number of visible photons (wavelengths of about 200–1000 nm) proportional to the gamma photon energy. The location of scintillation points is detected by the photomultiplier tube array coupled to the crystal through the light pipe. The whole system is configured in a hexagonal close packed arrangement such that the signal from a given scintillation event excites responses in at least seven photomultiplier tubes, i.e. a central tube and at least the six nearest tubes. Anger combined the magnitude of the signal from each photomultiplier tube to provide a two dimensional position signal indicative of the point of gamma ray absorption. This process required a large electronic system to compute all the coincidental responses from a large set of combinations of typically 72 elements taken 7 at a time.

Proposed improvements in recent years for overcoming the limitations of the Anger camera have included use of intensifier tubes, position sensing photomultiplier tubes, and arrays of solid state photodetectors, all with very limited success. The intensifier tube proposals have limited sensitivity and resolution because of insufficient gain and high background noise. An example of this type of camera is one proposed by Lo I. Yin (1979), in which the converting scintillation crystal is coupled directly to a fiberoptic faceplate which is coupled to an image intensifier tube. This camera is limited by insufficient gain in the photodetector to

cover a large area, and the photodetector must be scaled up to the size of the input crystal to achieve efficient light coupling. More recently, Dilmanian et al (IEEE transactions on Nuclear Science, 37 (1990)) described a gamma imaging system comprising an NaI crystal coupled by a fiberoptic taper to the entrance port of a Hamamatsu microchannel-plate imager (PIAS) photon counting imaging system. Although the imaging system demonstrated an autoradiograpic resolution of about 0.7 mm FWHM, it was limited in cross-sectional dimension to 26 mm. To scale this instrument up to Anger camera dimensions would be prohibitively expensive since conventional imagers have an active diameter of only 15 mm. A factor affecting the Dilmanian et al and similar imagers is that there is no pulse height selection on the detected gamma photon distribution events. This will result in degraded imaging of deep tissue due to Compton scattering, which confounds the gamma isotope distribution image.

An example solid state detector array type of gamma imager by Engdahl et al (U.S. Pat. No. 5,171,998) includes the usual front end gamma scintillator followed by an array of solid state photo-diode detectors, preferably low capacitance silicon drift elements. The impact of the gamma ray photon is tracked in two dimensions by a complex timing scheme on two coordinates. Although small arrays and imaging devices show some promise, limitations arise when making these arrays much larger. Because the photodiodes as described by Engdahl et al are to be directly mounted to the scintillator crystal or light pipe attached to it, there is the possibility of gamma ray photons striking directly on the photodiodes. This could have the effect of creating an intense background event structure which would be difficult to compensate.

Two limitations of the original Anger camera addressed by recent inventions include the inability of the Anger camera to distinguish pulse height and use of NaI as the scintillator. The first limitation does not permit the camera to reject multiple scatter gamma photons which confounds the isotope distribution image. The second is the use of NaI crystal for its blue spectrum center of its scintillation photons. This blue spectrum center was selected for optimum use of photomultiplier tubes which are more sensitive in the blue, although the visible photon yield is notably lower than that of other scintillator crystals. Also, NaI is fragile and hydroscopic, requiring careful handling.

The present invention solves or substantially reduces in critical importance problems with prior art camera structures by providing an inexpensive gamma camera which uses any of several well known gamma scintillation detector crystals such as thallium doped NaI or thallium doped cesium iodide (CsI). The increased photon yield of CsI(Tl), although further into the red spectrum, is a desirable attribute, and CsI is less fragile and easier to handle than NaI and is not hydroscopic. The invention further utilizes a novel high gain, low noise, high quantum efficiency intensifier system combined with a video signal processor to produce images of radioisotope distributions in the body.

It is therefore a principal object of the invention to provide an improved gamma imaging camera system.

It is a further object of the invention to provide a gamma imaging camera utilizing a scintillation crystal that permits retrofit to existing camera systems.

It is a further object of the invention to provide a gamma imaging camera system permitting use of CsI(Tl) as the scintillator crystal which is less fragile, less hydroscopic and has greater photon yield than NaI(Tl).

It is a further object of the invention to provide an economical and portable gamma camera having no light pipes for coupling the scintillator crystals and the photon detector.

It is another object of the invention to provide a gamma imaging camera incorporating a high efficiency coupling lens to capture the scintillation photons from a large area crystal and couple the signal to a small aperture sensor system.

It is a further object of the invention to utilize night vision inverter tube assemblies coupled and operated in a novel manner.

It is another object of the invention to provide a gamma camera having ultra low level detection capability with a gain of about 10^9 with noise less than 10^{-3}/pixel/sec.

It is another object of the invention to provide a gamma imaging camera wherein the image processing is simplified by using conventional video camera output with a VCR and personal computer control.

It is a further object of the invention to provide a gamma imaging camera incorporating Compton scatter rejection in the gamma image by thresholding in the image processing.

It is another object of the invention to provide a gamma imaging camera incorporating cosmic ray background rejection by band limiting of the scintillation events in the image processing.

It is yet another object of the invention to provide an ultra-low level (essentially single-photon) visible spectrum imaging camera system.

These and other objects of the invention will become apparent as a detailed description of representative embodiments thereof proceeds.

SUMMARY OF THE INVENTION

In accordance with the foregoing principles and objects of the invention, a gamma ray imaging camera system and method for using it are described which in representative embodiments comprise a gamma my collimator, a scintillator adjacent the collimator for converting gamma photons into visible photons, a low level visible photon detector including at least two optically coupled inverter tubes, a high-speed lens for imaging the visible photons onto the detector, a video imager for receiving, recording and storing sequential images of the visible photons defining the detector output, and a programmed computer for processing the images and determining the spatial distribution of the images.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be more fully understood from the following detailed description of representative embodiments thereof read in conjunction with the accompanying drawings wherein:

FIG. 1 is a schematic of the component parts of the gamma camera system of the invention;

FIG. 2 is a view in axial section of the lens system and low level imaging system of the FIG. 1 camera system;

FIG. 3 is a schematic block diagram of the essential components of the imaging device of the FIG 1 camera system; and

FIG. 4 is a flow diagram of the operational control process for the FIG. 1 camera system.

DETAILED DESCRIPTION

Referring now to the drawings, FIG. 1 shows a schematic layout of the component parts of representative gamma camera system **10** of the invention. System **10** may be configured for imaging radioisotope distributions in the human body. Gamma radiation (rays) **11**, such as from an isotope source distribution **12** within body B, may be directed onto system **10** as at entrance aperture **13** defined in light tight enclosure **14**. Collimator **15** is disposed at aperture **13** and comprises a high-Z material such as lead with an array of apertures **16** disposed perpendicularly to the plane of aperture **13**. It may be noted at the outset that in some gamma imaging applications, collimating the gamma rays may not be necessary. Accordingly, in one basic embodiment of the invention contemplated herein, gamma collimation means may be omitted. A gamma transparent visible light barrier **17** and scintillation crystal **19** are disposed adjacent collimator **15**. Scintillation crystal **19** converts gamma photons by the photoelectric effect into visible photons **21** of longer wavelength detectable by visible light photodetector devices. Scintillation crystal **19** may comprise any well known material conventionally used for this purpose, such as NaI(Tl), CsI(Tl), CeF_3, BaF_2, ZnS, ZnCdS(Ag) or other phosphors, xenon or other noble gas in gas or liquid form, or bismuth germinate, or crystal **19** may be a polycrystalline layer of scintillator material such as gadolinium oxysulfide activated with terbium or yttrium oxysulfide if low energy x-ray imaging is desired. However, CsI(Tl) may be preferred for gamma imaging because of a characteristic high visible photon yield per incident gamma. A high efficiency short focal length lens system **23** couples the signal defined by photons **21** to a novel ultra high gain, low noise imaging system (detector) **25**. Because of the typical large (about 30 cm) diameter of crystal **19**, the signal must propagate a distance of about 30 to 40 cm to lens system **23** in order to suitably demagnify the image dimension of source distribution **12**. This ratio is about 12:1 for a typical (305 mm diam) crystal used in nuclear medicine and the entrance port (25 mm diam) of a second or third generation night vision device. The aperture of lens system **23** must be large because the yield is only about 5,000 visible photons for the typical nuclear gamma photon (100 to 300 Key). If lens **23** has an aperture of 10 cm, this converts to a fractional interception at 34 cm spacing of $(10/34)^2$, i.e. less than about 10% of the event photon set intercepted. At a quantum efficiency of about 10%, the number of photons involved in production of the image per gamma event is about 40, although other factors might reduce this to about 10 to 20 detected visible photons per gamma photon. Lens system **23** and imaging system **25** must therefore have an extremely high gain with extremely low noise in order to render an image of the process. Video imaging device **27** (such as a vidicon or CCD device) transmits signal **28** to image processing system **29**.

FIG. 2 shows a detailed axial sectional view of lens system **23** and imaging system **24**. In a preferred embodiment suggested in the figures, lens system **23** comprises a three element anti-reflective coated system of two aspheric lenses **31,32** and one miniscus lens **33**. Aspheric lens **32** is 50 mm diameter with 40 mm focal length (e.g., Spindler Hoyer catalog #031746). Lens **33** is 80 mm diameter by 200 mm focal length spaced about 2 cm from lens **32**. Lens **31** may be the front 100 mm diameter aspheric element of a TV projection lens (e.g., US Precision lens Delta 101A), and is postioned about 3 cm from lens **33**. Lens system **23** functions most effectively for visible photons in the 300–900 nm range, and at an f number less than 1.0 and may be replaced

by other lens systems as would occur to one skilled in the applicable art guided by these teachings.

Lens system **23** is coupled at light fight seal **35** to imaging system **25**. The function of system **25** is to detect with high quantum efficiency and amplify light images with an amplification factor of about 10^9, but also to maintain the noise level to less than about 10^{-3} events/sec/pixel. In the FIG. **2** embodiment, system **25** comprises two commercially available night-vision inverter tubes **37,38** (e.g., Varo AN/PUS-4 IIIGen tube **37**; Varo 3603-1 IIGen tube **38**) coupled output to input at interface **39** between tubes **37,38** with a low temperature fluid **40** such as ethylene glycol. The IIIGen tube **37** has a gallium arsenide photocathode with very high quantum efficiency into the red (~900 nm), and is very effective with a wide range of scintillators, including CsI which emits red shifted visible photons for a gamma photon photoelectric event. A IIGen tube can be used in **37** if the scintillator is NaI(Tl) which emits predominately in the blue-green spectral region. The output of tube **37** is a fiber optic face plate coupled to the input of tube **38** which also has a fiber optic type window. This arrangement can be coupled and cooled to less than −20° C., including internal high voltage power supplies of the inverter tubes packaged with the tubes. The tubes are cooled by inserting the coupled tube assembly into heat conducting aluminum or copper cylinder **42** wrapped by a copper tube coil **43** having inlet/outlet **44/45** for conducting cooling fluid **47** (such as alcohol) from thermally insulated reservoir **48** using pump **49**. Cylinder **42** reduces electrical noise that would otherwise enter the system and uniformly cools tubes **37,38**. Fluid **47** temperature is reduced to about −20° C. by cryocooler element **50** in reservoir **48** transporting the cooling process over conduit **51** from cryocooler **52** (e.g., Neslab model CC100F). Other well known methods for low temperature cooling of detectors may be used, such as liquid nitrogen or Peltier effect devices, but the system shown in FIG. **2** may have much less vibrational noise than typical fan cooled Peltier devices and is simpler to handle than liquid nitrogen.

The cooled detector assembly is surrounded by thermal insulation material **54** (such as STYROFOAM) and light tight metal enclosure **55**. The inverter tubes are powered by an external low voltage power supply **57**. Region **59** between lens system **23** and entrance port **61** of imaging system is filled with inert gas such as nitrogen to insulate lens **32** (at room temperature) from the cooled detector **25** assembly. Conversely, region **59** may be evacuated. Photons **21** are projected by lens system **23** onto the entrance port **61** of first inverter tube **37**. The inverter tubes amplify the input light signal by photoelectron emission, acceleration, focusing and micro channel plate amplification. Because tube **37** has a gallium arsenide photocathode, system **25** has a very high quantum efficiency for red spectrum generating scintillation crystals such as CsI(Tl). These tubes provide a gain of about 30,000 each and, when coupled as shown, yield a gain of $30{,}000^2$ or about 10^9 as desired. The spontaneous thermal emission of all surfaces is drastically reduced when the system is cooled to less than −20° C.

The resultant amplified light signal **63** at output stage **65** of tube **38** is coupled by lens **67** onto a point **68** on CCD device **27**. Lens **67** also seals region **58** filled with inert gas such as nitrogen to insulate the lens from the cooled interior. Lens **67** is a close up lens that falls the field of device **27**. Output signal **69** of device **27** containing the positional and intensity information of the scintillation event is fed into image processing system **29** (FIG. **1**).

Referring now to FIG. **3**, shown therein is a schematic block diagram of the essential components of imaging processer **29**. Signal **69** from device **27** is first displayed on a real-time monitor **71**. The image comprises small star-like bursts indicating a gamma interaction or wide area bursts indicating typical cosmic ray background events. Signal **69** is also fed to a conventional video cassette recorder (VCR) **73** which is controlled in operation by computer (PC) **75** controlled from software storage unit **77**. The recorded video signal **79** is transmitted to a typical video image frame data acquisition plug-in board **72** (such as an Imaging Technology Vision Plus-AT OFG) within PC **75**. The computer program controls the data acquisition at VCR **73** by means of a computer I/O board **76** over control lines **78**, rendering the desired outputs at monitor **81** or readout device **83**.

Referring now to FIG. **4**, shown therein is a flow diagram of operational control process **90** for camera system **10**. Computer **75** starts and stops the video taping of the gamma imaging process, collects a thorough record of scintillation events produced by imaging system **27**, and then analyzes the images frame-by-frame. For each frame N in a sequence, computer **75** digitizes and stores a digital record of frame N and N−1 (FIG. **4**, block **92**). In the step labeled **96**, each pixel of frames N and N−1 is examined for the analog-to-digital conversion value. If the element $A_{ij}(N)$ is zero, zero is entered in a composite image $A_{ij}(N)^*$ of the Nth frame (block **100**). If $A_{ij}(N)$ is non-zero, the program tests to see (block **102**) if the $A_{ij}(N-1)$ at frame N−1 is zero. If the A_{ij} element at the previous frame is not zero, then the $A_{ij}(N)^*$ pixel of the composite frame is set to zero. This is done to eliminate an after image event from being registered multiple times in the composite frame. If, however, the $A_{ij}(N-1)$ of the previous frame is zero (block **102**) then computer **75** searches (block **104**) for non-zero pixels $A_{i+p,j+q}(N)$ adjacent to $A_{ij}(N)$ and to determine which of these are maximum. This is done to find the local maximum pixel representing the scintillation event. The magnitude of the pixels obtained (block **104**) is compared (block **108**) to a range $s<x<t$. The lower limit s and the upper limit t are preprogrammed into software storage unit **77**. The purpose of this selection process is to cancel scintillation events that are too low due to multiple scatter by a Compton process or too high and caused by a cosmic ray event. If the maximum pixel(s) do not satisfy this window criteria, zeros are entered in composite frame $A_{i+p,j+q}(N)^*$ (block **106**) or if the criterion is satisfied, a value of 1 is entered in the composite frame (block **110**). The process is repeated for all pixels for a given frame (block **112**) and composite frames are generated for each frame of the run under analysis (blocks **114,116**). Once all frames are tested, the program computes a super composite frame $B=A_{ij}(N)^*$ (block **94**). The resultant high quality image of the isotope distribution is then displayed (block **94**). Obtaining images of a time cycled process such as a beating heart can be greatly facilitated by this system by putting a time marker on the video recording synchronized with the process. Computer **75** is then directed to examine only those frames in a particular point in the cycle relative to the time marker and compose images with that subset of frames.

The invention therefore provides an improved gamma camera system having particular utility in the field of nuclear medicine. It is understood that modifications to the invention may be made as might occur to one with skill in the field of the invention within the scope of the appended claims. All embodiments contemplated hereunder which achieve the objects of the invention have therefore not been shown in complete detail. Other embodiments may be developed without departing from the spirit of the invention or from the scope of the appended claims.

I claim:

1. A gamma ray imaging camera system comprising:

(a) gamma ray collimating means;

(b) scintillation means adjacent said collimating means for converting gamma photons into visible photons;

(c) visible photon detection means including at least two optically coupled inverter tubes and means for cooling said inverter tubes;

(d) a lens for imaging said visible photons onto said detection means;

(c) video imaging means for receiving, recording and storing sequential images of said visible photons defining the output of said detection means; and

(f) means for determining the spatial distribution of said images of said visible photons.

2. The system of claim 1 wherein said means for determining the spatial distribution of said images includes a programmed computer for processing said images from said video imaging means and for interpreting the spatial distribution of said images.

3. The system of claim 1 wherein said scintillation means includes a scintillator material selected from the group consisting of thallium activated sodium iodide, thallium activated cesium iodide, cerium fluoride, barium fluoride, zinc sulfide, zinc cadmium sulfide, bismuth germanate, terbium activated gadolinium oxysulfide, yttrium oxysulfide, and the noble gases.

4. The system of claim 1 wherein said lens is a multiple element aspheric type.

5. A gamma ray imaging camera system comprising:

(a) scintillation means for converting gamma photons into visible photons;

(b) visible photon detection means including at least two optically coupled inverter tubes and means for cooling said inverter tubes;

(c) a lens for imaging said visible photons onto said detection means; and

(d) video imaging means for receiving, recording and storing sequential images of said visible photons defining the output of said detection means.

6. The system of claim 5 further comprising gamma ray collimating means adjacent said scintillation means.

7. The system of claim 5 further comprising means for determining the spatial distribution of said images including a programmed computer for processing said images from said video imaging means and for interpreting the spatial distribution of said images.

8. The system of claim 5 wherein said scintillation means includes a scintillator material selected from the group consisting of thallium activated sodium iodide, thallium activated cesium iodide, cerium fluoride, barium fluoride, zinc sulfide, zinc cadmium sulfide, bismuth germanate, terbium activated gadolinium oxysulfide, yttrium oxysulfide, and the noble gases.

9. The system of claim 5 wherein said lens is a multiple element aspheric type.

10. An ultralow light level imaging camera system, comprising:

(a) a camera lens;

(b) visible photon detection means including at least two optically coupled inverter tubes and means for cooling said inverter tubes; and

(c) video imaging means for receiving, recording and storing sequential images of said visible photons defining the output of said detection means.

11. The system of claim 10 wherein said camera lens is a multiple aspheric type.

12. The system of claim 9 further comprising means for determining the spatial distribution of said images including a programmed computer for processing said images from said video imaging means and for interpreting the spatial distribution of said images.

13. A method for gamma ray imaging comprising the steps of:

(a) providing a source of gamma rays;

(b) converting gamma photons from said source into visible photons;

(c) detecting and amplifying said visible photons using at least two cooled optically coupled inverter tubes;

(d) optically imaging said visible photons onto said coupled inverter tubes for providing sequential amplified images of said visible photons;

(e) storing said sequential amplified images of said visible photons; and

(f) determining the spatial distribution of said sequential amplified images of said visible photons.

14. The method of claim 13 wherein said step of determining the spatial distribution of said amplified images is performed using a programmed computer for processing said amplified images and for interpreting the spatial distribution of said amplified images.

15. The method of claim 13 wherein the step of converting gamma photons into visible photons is performed using scintillation means.

16. The method of claim 15 wherein said scintillation means includes a scintillator material selected from the group consisting of thallium activated sodium iodide, thallium activated cesium iodide, cerium fluoride, barium fluoride, zinc sulfide, zinc cadmium sulfide, bismuth germanate, terbium activated gadolinium oxysulfide, yttrium oxysulfide, and the noble gases.

* * * * *

US005521387A

United States Patent [19]

Riedner et al.

[11] Patent Number: 5,521,387

[45] Date of Patent: * May 28, 1996

[54] **RADIATION DETECTOR EMPLOYING SOLID-STATE SCINTILLATOR MATERIAL AND PREPARATION METHODS THEREFOR**

[75] Inventors: **Robert J. Riedner**, Waukesha; **Robert J. Lyons**, Milwaukee, both of Wis.; **Dominic A. Cusano**; **Charles D. Greskovich**, both of Schenectady, N.Y.

[73] Assignee: **General Electric Company**, Milwaukee

[*] Notice: The portion of the term of this patent subsequent to Nov. 8, 2005, has been disclaimed.

[21] Appl. No.: **649,332**

[22] Filed: **Feb. 1, 1991**

Related U.S. Application Data

[63] Continuation of Ser. No. 395,175, Aug. 18, 1989, abandoned, which is a continuation of Ser. No. 814,804, Dec. 30, 1985, abandoned.

[51] **Int. Cl.**[6] **C09K 11/78**

[52] **U.S. Cl.** ..... **250/367**; 252/301.17; 252/301.4 R; 501/152

[58] **Field of Search** ..... 252/301.4 R, 301.17; 250/367; 501/152

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Primary Examiner—Mark L. Bell
Assistant Examiner—C. M. Bonner
Attorney, Agent, or Firm—John H. Pilarski

[57] **ABSTRACT**

A polycrystalline ceramic scintillator exhibiting reduced afterglow includes between about 5 and 50 mole percent Gd_2O_3, between about 0.02 and 12 mole percent of either Eu_2O_3 or Nd_2O_3 as a rare earth activator oxide, and between about 0.003 and 0.5 mole percent of either Pr_2O_3 and Tb_2O_3 as an afterglow reducer. The remainder of the scintillator composition is Y_2O_3. The resulting scintillator is especially useful for a radiation detector of the type having a plurality of radiation receiving channels. A scintillator body is disposed in each channel so that radiation being received therein is incident on the scintillator body and causes the body to convert the incident radiation to light energy of a predetermined wavelength. The radiation detector also includes means for converting the light energy from the scintillator into electrical signals which are proportional to the amount of radiation incident on the scintillator body. Methods for preparing the scintillator of the present invention include sintering, sintering combined with gas hot isostatic pressing, and vacuum hot pressing.

21 Claims, 5 Drawing Sheets

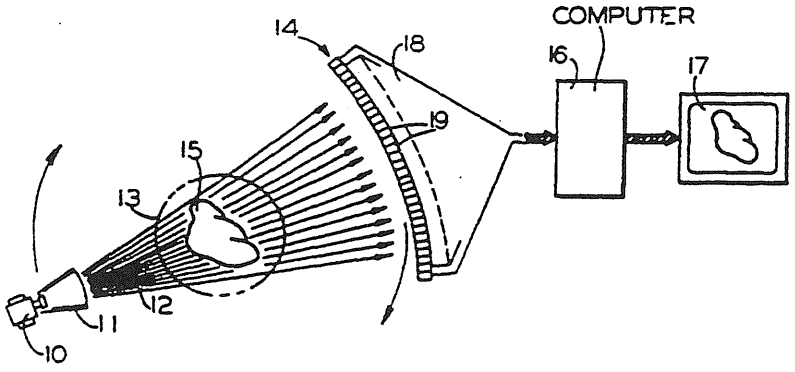

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Fig 1

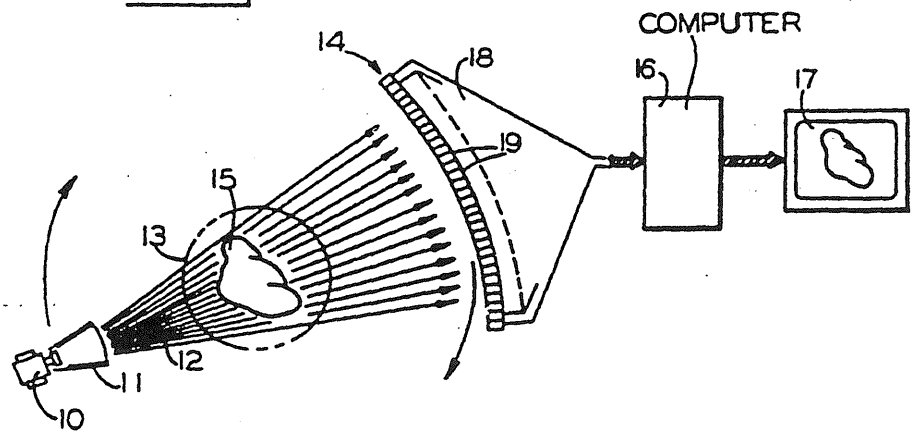
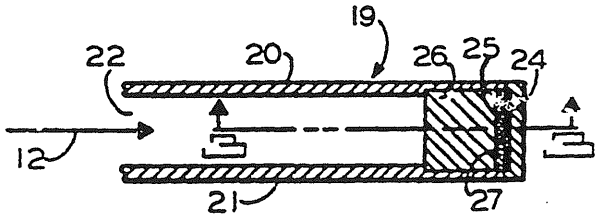


Fig 2



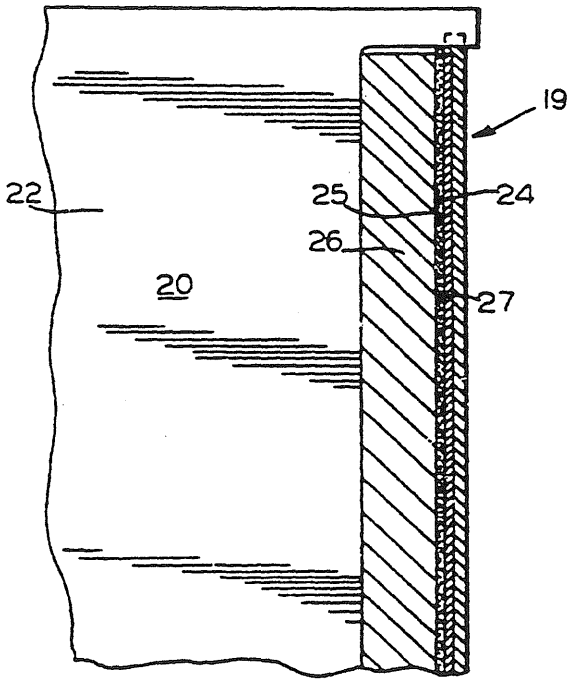


Fig 3

Fig 4

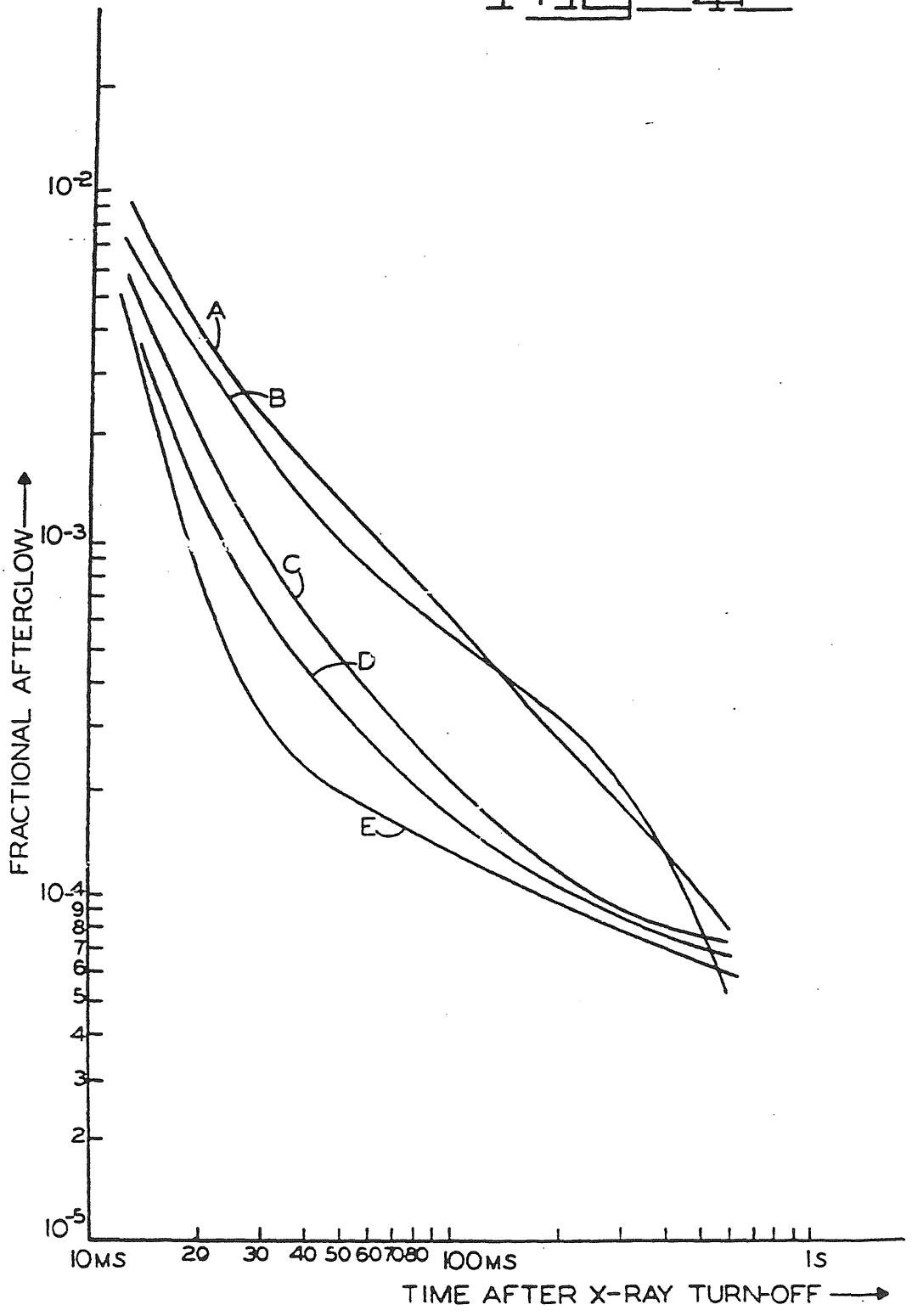

FRACTIONAL AFTERGLOW
10^{-2}
10^{-3}
10^{-4}
9
8
7
6
5
4
3
2
10^{-5}
A
B
C
D
E
10MS
20
30
40
50
60
70
80
100MS
1S
TIME AFTER X-RAY TURN-OFF

Fig 5

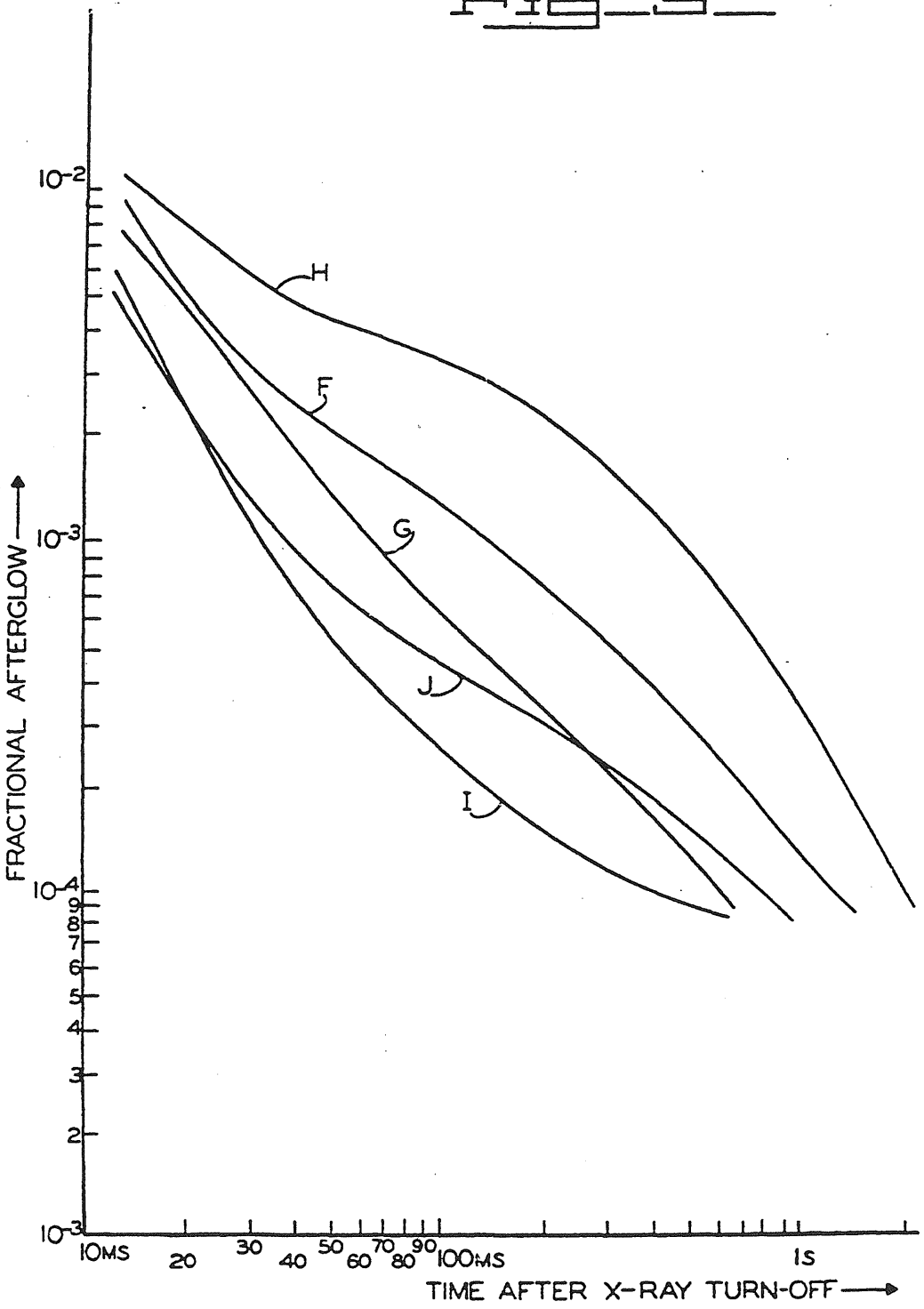
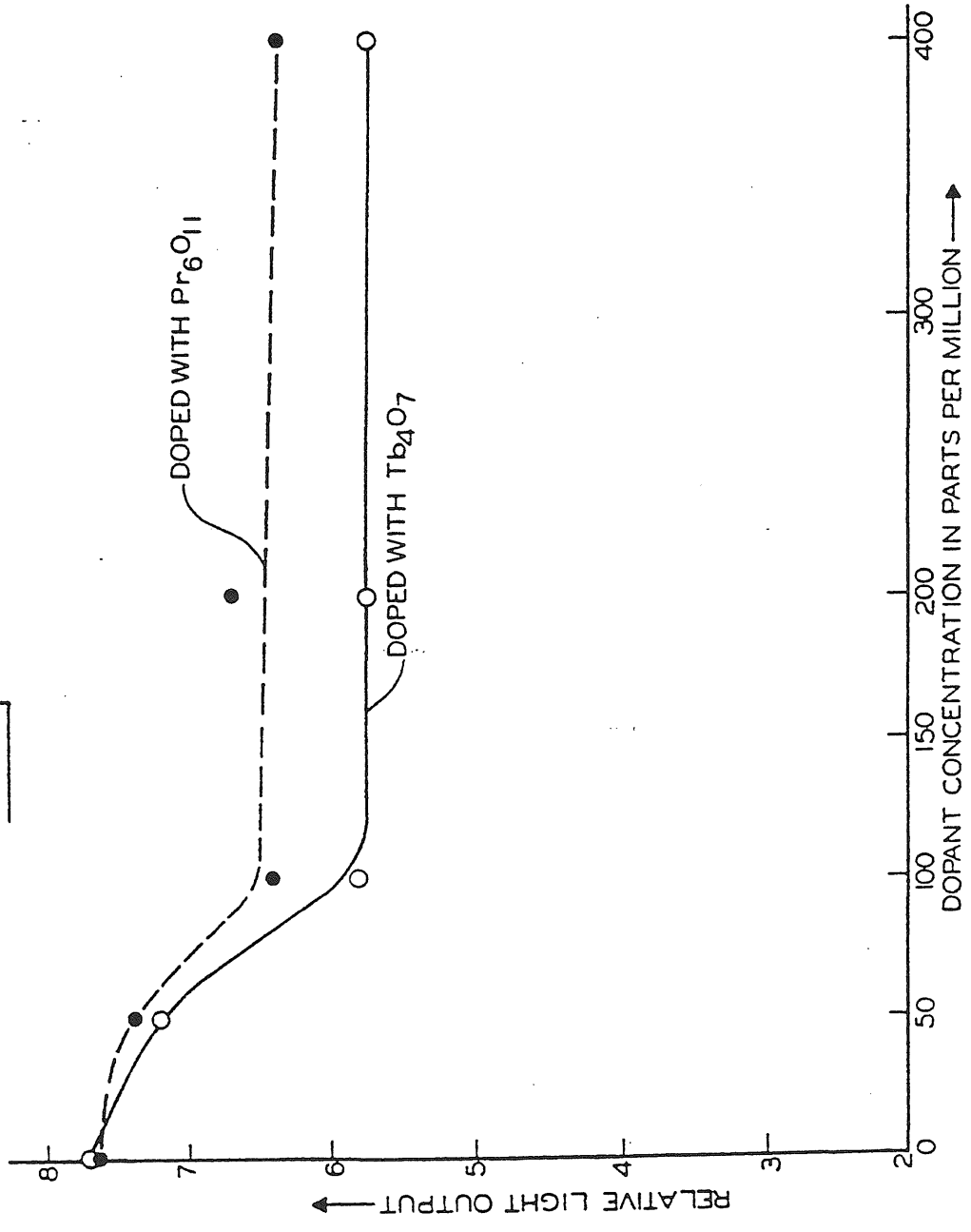

FRACTIONAL AFTERGLOW
10^{-2}
10^{-3}
10^{-4}
9
8
7
6
5
4
3
2
10^{-3}
H
F
G
J
I
10MS
20
30
40
50
60
70
80
90
100MS
1S
TIME AFTER X-RAY TURN-OFF

Fig. 6


DOPED WITH Pr_6O_{11}
DOPED WITH Tb_4O_7
RELATIVE LIGHT OUTPUT
DOPANT CONCENTRATION IN PARTS PER MILLION
0
50
100
150
200
300
400
2
3
4
5
6
7
8

Eu_2O_3 or Nd_2O_3 as a rare earth activator oxide, and between about 0.003 and 0.5 mole percent of at least one afterglow reducer selected from the group consisting of Pr_2C_3 and Tb_2O_3. The remainder of the scintillator composition is Y_2O_3. A radiation detector employing such a scintillator comprises a detector array housing having a plurality of channels defined therein, for receiving the radiation. A polycrystalline ceramic scintillator having the above composition is disposed in each channel so that radiation being received by the channel is incident on the scintillator body, and so that the incident radiation causes the body to scintillate at a predetermined wavelength. The detector also includes means for detecting the predetermined wavelength scintillator energy from each of the scintillator bodies, with the detecting means being coupled to each scintillator body so as to produce a set of signals related to the radiation received in the respective channels of the detector array housing. Methods for preparing the yttria-gadolinia ceramic scintillator of the present invention include sintering, vacuum hot pressing, and sintering combined with gas hot isostatic pressing.

BRIEF DESCRIPTION OF THE DRAWINGS

The subject matter which is regarded as the invention is particularly pointed out and distinctly claimed in the concluding portion of the specification. The invention itself, however, both as to its organization and its method of practice, together with further objects and advantages thereof, may best be understood by reference to the following description taken in conjunction with the accompanying drawings, in which:

FIG. 1 is a representational view depicting the elements of a typical CT scanner;

FIG. 2 is an end elevation, cross-sectional view schematically illustrating one channel of a radiation detector, in accordance with one embodiment of the present invention;

FIG. 3 is a cross-sectional view of the detector channel shown in FIG. 2, taken along line 3—3;

FIG. 4 illustrates graphically the effect on scintillator afterglow of increasing concentrations of Pr_2O_3;

FIG. 5 is a graph showing the effect on scintillator afterglow of increasing concentrations of Tb_2O_3; and

FIGS. 6 and 7 are graphical illustrations of the dependence of the relative light output of the scintillator on the concentration of either Pr_2O_3 or Tb_2O_3.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 shows in representational form the elements used in a typical CT scanner for the production, transmission, and detection of x-ray radiation. The scanner includes radiation source 10, for producing penetrating radiation. Radiation source 10 frequently comprises a rotating anode x-ray tube. The radiation produced by source 10 is collimated by collimator 11 to produce a thin beam of x-rays 12 which is projected through aperture 13 toward x-ray detector 14. A body to be examined, such as subject 15, is positioned within aperture 13 in the path of the fan beam of x-rays 12 in such a manner that the beam is attenuated as it passes through subject 15, with the amount of attenuation being dependent upon the density of subject 15. Radiation detector 14 comprises detector array housing 18 having a plurality of channels 19 defined therein. Channels 19 are configured so as to receive the attenuated fan beam of x-rays 12, and so as to produce electrical signals which are dependent on the intensity of the radiation received within each channel. The resulting electrical signals are therefore measures of the attenuation of the x-ray beam by the portion of the body through which the beam has passed.

In operation, electrical signal readings are taken from each channel 19 at a plurality of angular positions with respect to subject 15, while source 10 and detector 14 are rotated about aperture 13. The resulting readings are digitized and transmitted to computer 16, which uses one of a number of available algorithms to compute and construct a picture of the cross-section traversed by the fan beam of x-rays 12. The resulting picture is displayed on cathode ray tube 17, or, alternatively, may be used to create an image on permanent media such as photographic film or the like.

In an x-ray radiation detector, channels 19 typically comprise a plurality of collimated cells, with each cell being of the type schematically illustrated in FIG. 2. The cell width is defined by the distance between collimator plates 20 and 21, which plates define window 22 for receiving x-rays 12 along an incremental portion of the fan beam which the cell faces. As can be seen from a comparison of FIGS. 2 and 3, the cell width is considerably smaller than the cell length, that is, the dimension of the cell perpendicular to the plane of the fan beam. It is desirable to minimize the cell width in order to provide good spatial resolution of the fan beam. Typical cell dimensions in a practical radiation detector may be about 1 mm. for the cell width and about 20 mm. for the cell length, of which approximately 15 mm. is exposed to radiation. Polycrystalline ceramic scintillator body 26 is disposed in channel 19 so that x-ray radiation 12 being received by channel 19 is incident on scintillator body 26, by passing between collimator plates 20 and 21 and impinging upon scintillator body 26. This incident radiation causes body 26 to scintillate at a predetermined wavelength, thereby converting the incident radiation into lower energy radiation in the visible or near-visible spectrum. The radiation detector of the present invention further comprises means for detecting the predetermined wavelength scintillator energy from each scintillator body 26. The scintillator energy detecting means is coupled to each scintillator body 26 so as to produce a set of signals which are proportional to the intensity of the radiation received in each of the respective channels 19 of the detector array. In the embodiment illustrated in FIGS. 2 and 3, photodiode assembly 24 is mounted behind scintillator body 26. Active surface 25 of photodiode assembly 24 is disposed so as to underlie scintillator 26 and to receive the scintillaton radiation which body 26 produces. Various means are available for directing the light produced by scintillator 26 to active surface 25 of photodiode 24. For example, all of the faces of scintillator body 26, except the face adjacent to photodiode 24, may be treated to reflect inwardly any light incident upon those treated faces. In the embodiment shown in FIGS. 2 and 3, optical coupling material 27 is also employed. Coupling material 27 is disposed between scintillator 26 and photodiode 24 so as to enhance coupling of the light produced by scintillator 26 to active surface 25 of photodiode 24.

U.S. Pat. No. 4,421,671 and U.S. application Ser. No. 629,027, referenced above, disclose a class of polycrystalline ceramic scintillator bodies which are generally useful for CT and other x-ray detecting applications. The scintillators disclosed therein are made up of rare earth yttria-gadolinia hosts and trivalent rare earth activator oxides. The scintillator compositions may also include one or more of the transparency promotors and light output restorers described in those patents. The finished scintillator bodies

are comprised of a cubic solid solution of the various chemical constituents.

Each of the scintillator compositions disclosed in the above-referenced documents includes Gd_2O_3, Y_2O_3, and at least one rare earth activator oxide. The resulting scintillator bodies have high x-ray stopping power, high radiant efficiency, high density, high uniformity, cubic structure, and are translucent-to-transparent in optical clarity. As used herein, the terms "transparent" and "translucent" refer to various degrees of optical clarity in the scintillator material. The cubic crystal structure of the disclosed scintillators provides the scintillator materials with optical attenuation coefficients typically less than 100 cm. -1, as measured by standard spectral transmittance tests on a polished scintillator material plate at the luminescent wavelength of the respective ion. Cubic materials are optically isotropic, that is, they have the same refractive index in all directions. Accordingly, light travelling through a cubic crystal structure consisting of a solid solution material follows a relatively short optical path. As a result, transparency and light output are enhanced. The scintillator compositions disclosed in the above-referenced documents can be made to be very dense, and, consequently, exhibit high x-ray stopping power. Stopping power is measured in terms of the distance an x-ray photon penetrates into the scintillator prior to its absorption. The absorbed x-ray photons are converted to optical wavelength photons which are detectable by photosensors. The x-ray stopping length of rare-earth-doped yttria-gadolinia polycrystalline ceramic scintillators is primarily dependant on Gd_2O_3 content, and increases with increased Gd_2O_3 concentration. A minimum of about 5 mole percent of Gd_2O_3 is needed in such scintillator compositions in order to meet the x-ray stopping power requirements for most practical detector designs. Finally, the luminescent efficiency of the scintillator compositions described above is enhanced by properly choosing the rare earth activator dopant. The combination of the rare earth activator oxide and the yttria-gadolinia host results in a scintillator which converts incident radiation into light output at a wavelength compatible with available photosensitive devices, and at a reasonable conversion efficiency.

In accordance with the present invention, scintillator body 26 employed in the type of radiation detector illustrated in FIGS. 2 and 3, has a composition consisting essentially of between about 5 and 50 mole percent Gd_2O_3 between about 0.02 and 12 mole percent of a rare earth activator oxide selected from the group consisting of Eu_2O_3 and Nd_2O_3, and between about 0.003 and 0.5 mole percent of at least one afterglow reducer selected from the group consisting of Pr_2O_3 and Tb_2O_3. The remainder of the scintillator composition is Y_2O_3. As used in the scintillator composition of the present invention, praseodymium and terbium function to reduce the luminescent afterglow of the scintillator material. Such afterglow is undesirable in radiation detectors for CT systems, because it leads to undesirable distortion of, and the presence of artifacts in, the reconstructed images. The afterglow phenomenom is divisable into primary or fundamental afterglow and secondary afterglow. Primary afterglow is of relatively short duration, and is thought to be associated with the specific rare earth activator involved. Secondary afterglow may be several times longer than the primary decay time, and is probably associated with the presence of additional electron-hole trapping centers created by native defects and/or low level impurities at various sites in the host crystal. It has been found that afterglow may be reduced by the addition of compensating dopants to the other constituents of the scintillator material. It is believed that the added dopants reduce afterglow by forming killer centers, which centers compete with the activator centers for electron-hole pairs that otherwise combine radiatively at the activator centers to produce luminescent output. For the scintillator compositions described in U.S. Pat. No. 4,421,671 and in U.S. application Ser. No. 629,027, Yb_2O_3, SrO and CaO were disclosed as dopants that may be added to the described compositions in order to reduce luminescent afterglow. Praseodymium and terbium were not recognized in those documents as being effective afterglow reducers. To the contrary, praseodymium and terbium were included among the list of rare earth elements which may be added to the basic yttria-gadolinia system as activators to enhance scintillator efficiency. The present inventors have discovered that, if either praseodymium or terbium is added to rare-earth-doped, yttria-gadolinia scintillator material, there is a significant improvement in scintillator afterglow. Unexpectedly, it has been determined that adding these elements in even such minute quantities as 0.003 mole percent produces a reduction in afterglow. More specifically, the present inventors have found that adding as little as 50 parts per million (ppm) of either praseodymium oxide or terbium oxide to a composition consisting of between about 5 and 50 mole percent gadolinium oxide and between about 0.02 and 12 mole percent of either europium oxide or neodymium oxide, with the remainder being yttrium oxide, significantly improves the afterglow characteristics of the material.

Referring now to FIG. 4, the effect produced on the scintillator afterglow by adding various concentrations of praseodymium oxide to the scintillator composition is graphically illustrated. The curves labeled A, B, C, D, and E in FIG. 4 depict the fractional afterglow (vertical axis) remaining at times greater than 10 milliseconds following the cessation of x-ray excitation (horizontal axis), for various afterglow reducer concentrations. Curve A is a plot of the afterglow data for a scintillator composition having 30 mole percent Gd_2O_3, 3 mole percent Eu_2O_3, and 67 mole percent Y_2O_3. For curves B through E various concentrations of praseodymium oxide were added to this baseline composition. Curves B through E depict the fractional afterglow data for scintillator compositions which contained 0.004, 0.008, 0.016, and 0.032 mole percent praseodymium oxide, respectively, and correspondingly less yttrium oxide. (These mole percentages of praseodymium oxide correspond to concentrations of 50, 100, 200 and 400 parts per million, respectively.) Each of the scintillator materials was processed as follows. The oxide compounds of gadolinia, europia and yttria were disolved in nitric acid to form a nitrate solution. For compositions containing praseodymium oxide, Pr_6O_{11} was also dissolved in nitric acid. These two nitrate solutions were then mixed and added to a supersaturated solution of oxalic acid to produce a co-precipitated crystalline oxalate powder. The oxalate powder was washed and dried, and then calcined by heating it in air at 800° C. to form the desired oxide powder. The resulting oxide powder was then pressed into disks and sintered at approximately 2,000° C. to form the scintillator bodies. For each body, the light output and the luminescent afterglow under 68 keV x-ray radiation were measured and plotted. It is readily apparent from FIG. 4 that increasing the concentration of praseodymium oxide in the scintillator composition produces increasingly reduced scintillator afterglow. For example, at about 50 milliseconds after x-ray turn-off, fractional afterglow for a scintillator material containing 0.032 mole percent praseodymium oxide (curve E) is only approximately 0.02 percent of its value immediately upon termination of x-ray excitation, as compared to about 0.13

percent for a material without praseodymium oxide (curve A).

FIG. 5 illustrates similar results when terbium oxide is used as an afterglow reducer, in place of praseodymium oxide. Curve F is plot of afterglow data for a scintillator composition of 30 mole percent Gd_2O_3, 3 mole percent Eu_2O_3, and 67 mole percent Y_2O_3. (Curve F was obtained using a different sample of material than was used for Curve A.) Curves G through J show the afterglow characteristics for similar scintillator materials which additionally contain 0.0035, 0.007, 0.014, and 0.028 mole percent terbium oxide, respectively, and correspondingly less yttrium oxide. (These molded percentages of terbium oxide correspond to concentrations of 50, 100, 200, and 400 parts per million, respectively.) Each of these samples was processed in the same manner as described above in relation to FIG. 4, with Tb_4O_7 being used in place of Pr_6O_{11}. (It should be understood that Pr_6O_{11} and Tb_4O_7 are converted to dissolved Pr_2O_3 and Tb_2O_3, respectively, in the scintillator composition upon heat treatment of the scintillator material during such preparation methods as, for example, sintering, vacuum hot pressing, and sintering combined with gas hot isostatic pressing.) With the exception of curve H, the data illustrated in FIG. 5 shows that increasing the concentration of terbium oxide in the scintillator material increasingly reduces scintillator afterglow. Curve H, for the sample containing 0.007 mole percent terbium oxide, exhibits an unusually high afterglow which, it is believed, is associated with foreign contamination of unknown origin. At about 50 milliseconds after x-ray turn-off, the sample containing 0.014 mole percent terbium oxide (Curve J) exhibited approximately 0.053 percent of the luminescence present immediately after x-ray shut-off, as compared with about 0.2 percent fractional afterglow for the sample without terbium oxide (Curve F).

The present inventors have also made determinations of the fractional afterglow of scintillator compositions employing neodymium as the rare earth activator, in place of europium. The processing techniques used to form the various materials into a scintillator body and the measurement methods employed to obtain the fractional afterglow data were similar to those described hereinabove in relation to FIGS. 4 and 5. For a scintillator composition of 30 mole percent Gd_2O_3, 69.9 percent Y_2O_3, and 0.1 mole percent Nd_2O_3, the addition of a small amount of praseodymium oxide had no significant effect on scintillator afterglow. At approximately 160 milliseconds after x-ray turn-off, the fractional afterglow of the scintillator composition without praseodymium was about 0.3 percent. When about 0.008 mole percent of praseodymium oxide was added to the composition, and the amount of yttrium oxide was correspondingly reduced, the afterglow at 160 milliseconds was virtually unchanged. However, for a scintillator material containing 0.25 mole percent Nd_2O_3, a significant reduction in scintillator afterglow was observed when praseodymium oxide was added to the base composition. At 160 milliseconds after x-ray turn-off, a scintillator composed of 30 mole percent Gd_2O_3, 69.75 mole percent Y_2O_3, and 0.25 mole percent Nd_2O_3 exhibited a fractional afterglow of 1.3 percent. When 0.008 mole percent of praseodymium oxide was added to this composition in place of a corresponding amount of Y_2O_3, the fractional afterglow after the same elapsed time was 0.2 percent, which represents about a six-fold improvement. Another scintillator sample, having the same composition of 0.25 mole percent Nd_2O_3, 69.75 percent Y_2O_3, and 30 mole percent Gd_2O_3, was prepared using higher purity materials and exhibited an afterglow of 0.04 percent at 160 milliseconds after x-ray turn-off. When praseodymium oxide in a concentration of 0.08 mole percent was added to this last scintillator composition in place of a corresponding amount of Y_2O_3, the scintillator afterglow at 160 milliseconds was reduced to 0.018 percent.

The reduction in luminescent afterglow that is achieved by the addition of either praseodymium oxide or terbium oxide to the rare-earth-doped yttria-gadolinia ceramic scintillator of the present invention is accompanied by a reduction in the light output of the scintillator, in response to incident x-ray radiation. However, at least for the concentrations claimed by the present applicants, the reduction in light output is not so severe as to be unacceptable. FIG. 6 graphically illustrates the dependence of relative light output of the scintillator on the concentration of either praseodymium oxide or terbium oxide in the scintillator composition, for relatively small dopant concentrations. The data shown in FIG. 6 were obtained using a base scintillator composition of 30 mole percent Gd_2O_3, 3 mole percent Eu_2O_3, and 67 mole percent Y_2O_3. The light output as a function of dopant concentration was obtained by adding increasing concentrations of terbium oxide and praseodymium oxide to the base material in place of corresponding amounts of Y_2O_3. The scintillator samples were prepared in accordance with the processing techniques described hereinabove in relation to FIGS. 4 and 5, and the light output of each sample was measured under 68 keV x-ray radiation. It can be seen from FIG. 6 that doping the base composition with 100 parts per million (ppm) of praseodymium oxide, which corresponds to approximately 0.008 mole percent of the scintillator composition, reduces the relative light output of the scintillator by about 17 percent. Doping the base composition with 100 ppm of terbium oxide, which corresponds to approximately 0.007 mole percent of the scintillator composition, causes a drop in light output of about 24 percent. FIG. 7 shows similar light output data for higher concentrations of the praseodymium and terbium dopants. The data shown therein were obtained using the same base scintillator composition of 30 mole percent Gd_2O_3, 3 mole percent Eu_2O_3, and 67 mole percent Y_2O_3.

The relative light output data depicted in FIGS. 6 and 7 indicate that increasing the concentration of either praseodymium oxide or terbium oxide in the scintillator composition increasingly reduces the scintillator light output in response to a given source of excitation radiation. For applications such as CT and DR, the scintillator light output can be of paramount importance. Where it is desirable to minimize the reduction in scintillator light output while simultaneously obtaining the benefit of improved afterglow characteristics, it is preferable to limit the concentrations of praseodymium oxide and terbium oxide to less than about 500 ppm (approximately 0.04 mole percent). For many conventional CT systems, the dual objectives of maintaining high light output and reducing luminescent afterglow can be achieved by limiting the concentration of the afterglow reducer to less than about 200 ppm (approximately 0.016 mole percent). The present inventors have found that the addition of 150 ppm (approximately 0.012 mole percent) praseodymium oxide to a scintillator composition made up of 30 mole percent Gd_2O_3, 3 mole percent Eu_2O_3, and 66.988 mole percent Y_2O_3 provides an extremely useful CT scintillator material having both good light output and improved afterglow characteristics.

Either europium or neodymium may be used in the scintillator composition of the present invention to function as an activator for enhancing scintillator efficiency. Generally, the rare earth activator concentration may range between 0.02 and 12 mole percent. Optimum concentration

of Eu_2O_3 is between about 1 and 6 mole percent. Nd_2O_3 is preferably added in concentrations of between about 0.05 and 1.5 mole percent. The radiation conversion characteristics and the decay speed of the resulting scintillators are somewhat different for a europium activator than they are for a neodymium activator. When europium is employed, the principal emission wavelength is about 611 nm, and the primary decay speed is on the order of 1 millisecond. The emission wavelength of 611 nm is very near the peak response of the PIN-type photodiodes which are typically used in CT applications. When neodymium is employed as the activator, the principal emission wavelength is in the infrared region, and the primary decay speed is on the order of about 0.4 milliseconds. Accordingly, neodymium offers a faster response scintillator, at the expense of some loss in detector efficiency due to somewhat of a mismatch between the principal emission wavelength of the scintillator and the peak response of PIN-type photodiodes.

The concentration of Gd_2O_3 may generally range between about 5 mole percent and 50 mole percent. As noted hereinabove, materials containing less than about 5 mole percent Gd_2O_3 exhibit x-ray stopping power which is insufficient for most practical detector designs. Materials having more than about 50 mole percent Gd_2O_3 become increasingly monoclinic in crystalline structure. Such materials are characterized by lower relative light outputs and poor optical clarity, due to grain boundary cracking and non-uniform crystalline structure. Materials having such non cubic structure suffer from appreciable light scattering and reabsorption due to a relatively longer effective light path length, which decreases the amount of light available for detection by external photosensors. The preferred range of Gd_2O_3 concentration is between about 20 and 40 mole percent.

The ceramic scintillators of the present invention may be prepared by sintering, sintering plus gas hot isostatic pressing, and vacuum hot pressing techniques. A preliminary step in the fabrication of the scintillator by any of these methods is the preparation of a suitable powder containing the desired scintillator material constituents. In one method for preparing such a powder, submicron-to-micron powders of yttria and gadolinia having purities of, for example, 99.99 percent to 99.9999 percent are mixed with the desired rare earth activators in the form of oxides, oxalates, carbonates, or nitrates, and mixtures thereof. The selected constituents may be mixed in an agate mortar and pestle or in a ball mill using water, heptane, or alcohol as liquid vehicles. Dry milling may also be used for mixing and for breaking up powder aggregates, and preferably includes employing a grinding aid such as 1 to 5 weight percent of stearic acid or oleic acid to prevent powder packing or sticking inside the ball mill. If any of the chemical constituents are added in the form of nitrates, carbonates, or oxalates, a calcining step is required to obtain the corresponding oxides prior to fabrication of the ceramic scintillator by any of the methods described hereinbelow.

A wet chemical oxalate method may also be employed to obtain the desired scintillator starting powder. The various materials may be dissolved in nitric acid to form nitrates, or the selected molar percentages of the nitrates of the predetermined chemical constituents may be dissolved in water. The nitrate solution of the desired scintillator material constituents is added to an oxalic acid solution which is, for example, 80 percent saturated at room temperature, resulting inco-precipitation of the respective oxalates. These oxalates are washed, neutralized, and filtered and may be dried in air at about 100° C. for approximately eight hours. The oxalates are then calcined by heating them in air to between about 700° C. and 900° C. for a time ranging from one to four hours, to form the corresponding oxides. Preferably, if either the hot pressing or the sintering method is to be used to prepare the scintillator, the oxalates and/or the resulting oxides are milled by one of several methods, such as ball, colloid, or fluid energy milling, to enhance optical clarity. It should also be noted that the optical clarity of the scintillator is typically improved by milling, regardless of the preparation method employed.

One method for preparing the ceramic scintillator of the present invention comprises preparing a multicomponent powder of preselected powder constituents by one of the powder preparation methods outlined above, and then pressing the powder into powder compacts. The powder compacts may be formed either by die pressing at pressures between about 3,000 psi and 15,000 psi, or by die pressing followed by isostatic pressing at between about 10,000 and 125,000 psi, in order to further increase the density of the powder compact. As a final step, the powder compact is sintered to yield a transparent-to-translucent polycrystalline ceramic scintillator body. The sintering step is conducted by heating the compact in vacuum or in a reducing or oxidizing atmosphere at a rate of between approximately 100° C. per hour and 700° C. per hour, to the sintering temperature of between about 1,800° C. and 2,100° C. This sintering temperature is held for between about one and 30 hours, and then the compacts are cooled to room temperature over a period of time ranging from about two to ten hours. Alternatively, the sintering sequence may include a hold step at a temperature lower than the final sintering temperature. For example, the powder compact may be heated at a rate of between about 300° C. per hour and 400° C. per hour to a holding temperature of between about 1,600° C. and 1,700° C. After a holding period ranging from about 1 hour to 20 hours, the temperature may be raised at a rate of between about 25° C. per hour and 75° C. per hour, to a temperature between about 1,800° C. and 2,100° C., for final sintering for a period of between about 1 and 10 hours. Additionally, if any grinding aids or compaction aids were used in the powder preparation and pressing steps, an oxidation treatment to remove all organic additives may be employed prior to the sintering phase. Furthermore, if the resulting scintillator is discolored due to, for example, oxygen deficiency in the sintering atmosphere, the ceramic may be made transparent to visible light by a suitable oxidation treatment. As an example, the scintillator may be heated for between about 1 and 20 hours at a temperature between about 800° C. and 1,200° C. in an oxygen-containing atmosphere.

A second method for preparing the ceramic scintillators of the present invention involves a combination of the processes of sintering and gas hot isostatic pressing (GHIP). Although the starting oxide powder may be prepared by either of the powder preparation methods described hereinabove, the oxalate co-precipitation method is preferred for this second method of preparing the scintillator. However, milling of the oxalate and/or oxide powders is not required in order to produce transparent ceramics by the process of sintering combined with GHIP. After preparation of the powder, a powder compact is formed by cold pressing at pressures of between about 3,000 and 10,000 psi, followed by isostatic pressing at pressures of between 15,000 and 125,000 psi. The powder compact is presintered to between 93 and 98 percent of its theoretical density, by heating the compact for between about 1 and 10 hours at a temperature between about 1,500° C. and 1,700° C. The presintered compacts are then gas hot isostatically pressed at pressures between about 1,000 psi and 30,000 psi and at temperatures

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United States Patent [19]

Spivey et al.

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[54] X-RAY IMAGE SENSOR

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[73] Assignee: Thermotrex Corporation, San Diego, Calif.

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[51] Int. Cl.[6] G01T 1/24; H01L 27/14

[52] U.S. Cl. 250/370.09; 250/580; 250/208.1

[58] Field of Search ..... 250/370.08, 370.09, 250/370.14, 58[illegible] 208.1; 378/98.8

[56] References Cited

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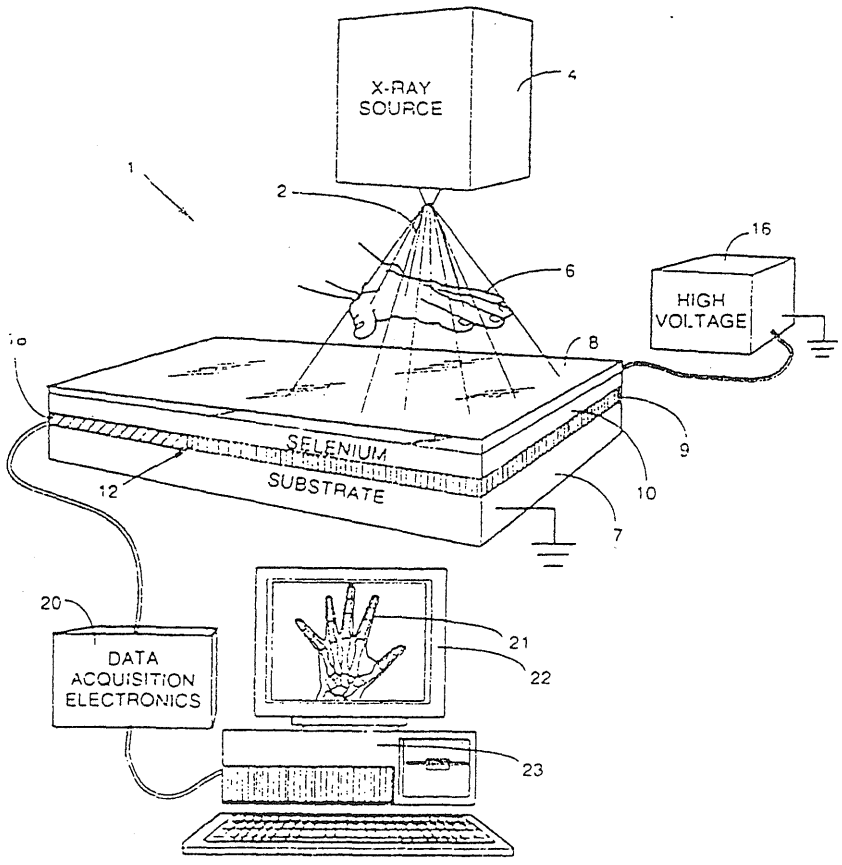
[57] ABSTRACT

This invention provides an imaging system for producing images from electromagnetic radiation such as x-rays. The system includes a detector comprised of a radiation-absorbing layer sandwiched between an array of CMOS integrated circuits (which we call pixel circuits) and a surface electrode layer transparent to the radiation. Each of the pixel circuits in the array has a charge collecting electrode. An external voltage applied between the surface electrode layer and the charge collecting electrodes produces an electric field across the thickness of the absorbing layer. Radiation passing through the transparent surface electrode layer is absorbed in the absorbing layer creating electron/hole pairs in the absorbing layer. A portion of the liberated holes (or electrons) migrates under the influence of the electric field toward the charge collecting electrodes, which collect the holes and store them as charges on small capacitors located within each circuit. This process results in a discrete distribution of stored voltages across the array proportional to the distribution of radiation photons incident on the absorbing layer. Circuitry in each pixel provides for the voltage on each pixel capacitor to be recorded via readout circuitry and permits the resetting of the pixel capacitors. Preferred embodiments provide fine resolution with a large number of pixels with dimensions about the size of the thickness of human hair.

49 Claims, 17 Drawing Sheets



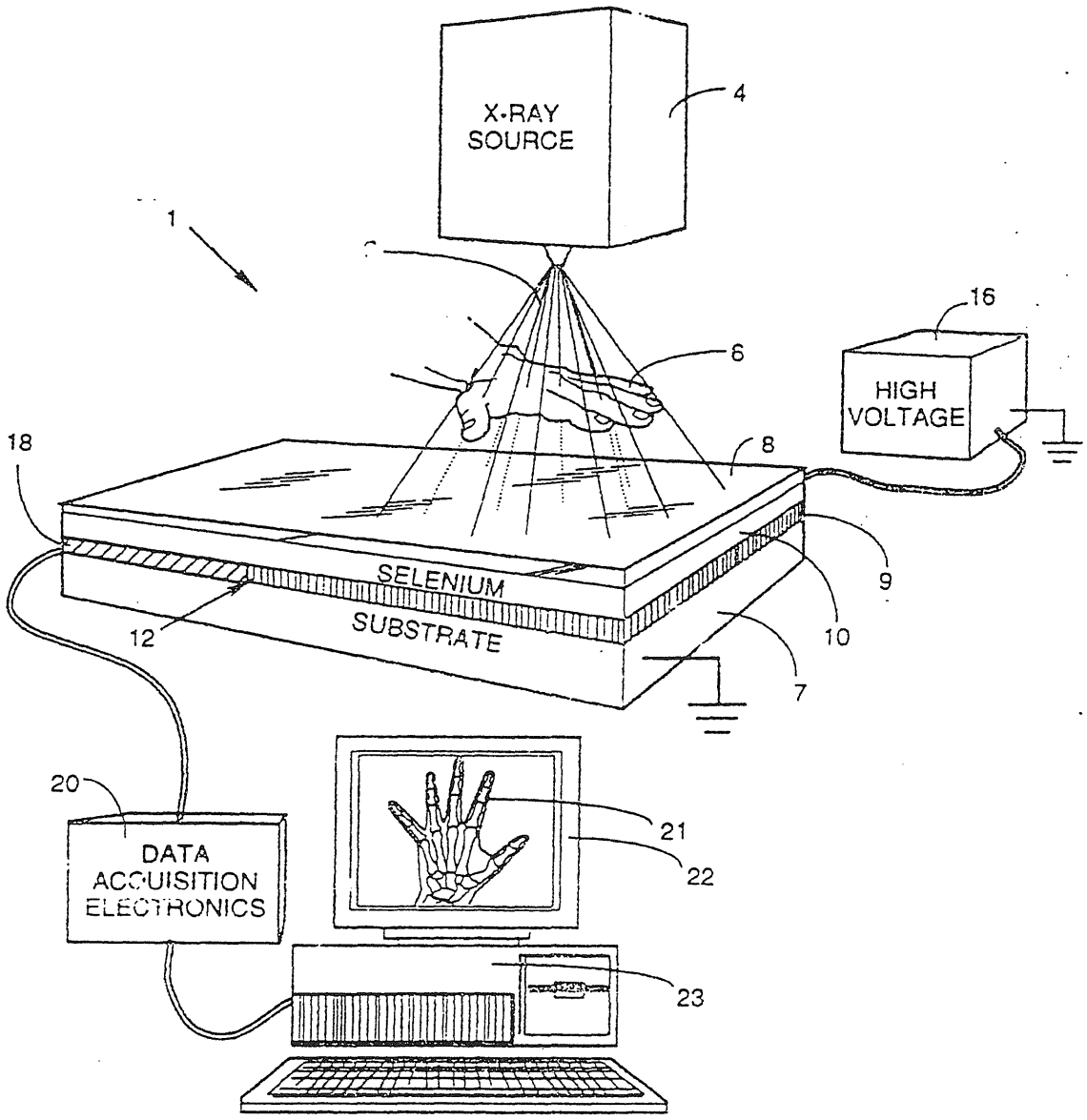

X-RAY SOURCE
4
1
6
16
HIGH VOLTAGE
18
8
9
SELENIUM
SUBSTRATE
12
10
7
20
DATA ACQUISITION ELECTRONICS
21
22
23

FIG. 1

X-RAY IMAGE SENSOR

The present invention relates to imaging devices and specifically to devices forming images from radiation.

BACKGROUND OF THE INVENTION

Film-screen x-ray imaging devices employing photographic film are widely used for medical imaging. However, the film is often overexposed in some areas and underexposed in other areas due to the limited range of contrast of the film combined with the thickness and composition variations of the tissue across the image. Discrimination of contrast differences of soft tissue in the overexposed and underexposed areas of the film can be difficult. This problem is especially apparent in film-screen mammography.

Attempts have been made at replacing film with electronic image sensors. Potential advantages of electronic image sensors over film include more accurate measurement of x-ray intensity over greater ranges, ability to digitize the image data, ease of archiving and transmitting image data, and improved display capabilities.

However, widespread clinical deployment of digital x-ray radiology has been hampered by the lack of a relatively inexpensive, compact, digital x-ray image sensor of sufficient image size and resolution. Present digital x-ray imaging systems typically use a fluorescing plate that converts each x-ray photon into a large number of visible light photons to produce a visible light image. The visible light image is then imaged onto an optical image sensor such as a CCD. The imaging performance of these techniques is degraded by relatively low x-ray to visible light conversion efficiencies, low collection efficiencies of the light photons, additional quantum noise from the light photons, and loss of resolution due to light spreading in the x-ray to visible light converter.

It is known that selenium is a photoconductive substance, i.e. x-ray photons absorbed in a layer of selenium exposed to an electric field will create a number of electron/hole pairs permitting a current to flow through the otherwise insulating layer. Xerox Corporation developed an x-ray imaging device in which an x-ray induced charge distribution on a selenium-coated aluminum plate is recorded with a paper/toner process. Philips Corporation presently markets a chest x-ray imager in which an x-ray induced charge distribution on a selenium-coated aluminum plate is recorded with scanning electrometers.

Complimentary metal oxide semiconductor (CMOS) fabrication technology is a well established industry which involves fabricating integrated circuits on and in the upper surface of a wafer of crystalline silicon. CMOS technology utilizes the silicon of the substrate wafer as the semiconductor material for transistor fabrication. The high mobility of charge carries in single-crystal silicon results in fast, compact, low-noise circuitry. Wafers with dimensions as large as six inches are available for large area CMOS circuits.

Thin film transistor (TFT) technology is an emerging semiconductor fabrication technology in which transistors are fabricated using a thin film of semiconductor material such as amorphous silicon, polycrystalline silicon or amorphous cadmium selenide deposited on an insulating substrate. An advantage of TFT technology is the potential for large area circuits. However, the disordered molecular structure of these thin films leads to low charge mobility which limits performance. In comparison with CMOS circuits, TFT circuits are generally slow and noisy with large leakage currents.

Various approaches are presently being proposed and investigated for directly acquiring a digital x-ray image. For example, Zhao and Rowlands (Proc. SPIE 1993; 1896:114–120) have proposed a readout array fabricated using cadium selenide TFT technology with an amorphous selenium coating. Tran et. al. disclose, in U.S. Pat. No. 5,235,195, TFT array circuits coated first with a "planarization" layer which in turn is coated with an energy-sensitive layer.

SUMMARY OF THE INVENTION

This invention provides a digital imaging system for producing images from electromagnetic radiation such as x-rays. The system includes a detector comprised of a radiation absorbing layer sandwiched between an array of CMOS integrated circuits (which we call pixel circuits) and a surface electrode layer transparent to the radiation. Each of the pixel circuits in the array has a charge collecting electrode. An external voltage applied between the surface electrode layer and the charge collecting electrodes produces an electric field across the thickness of the absorbing layer. X-ray photons pass through the transparent surface electrode layer and are absorbed in the absorbing layer creating electron/hole pairs in the absorbing layer. A portion of the liberated electric charge migrates under the influence of the electric field toward the charge collecting electrodes which collect charge and store these charges in small capacitors located within each circuit. This process results in a discrete distribution of stored voltages across the array proportional to the distribution of x-ray photons incident on the absorbing layer. Circuitry in each pixel provides for the voltage on each pixel capacitor to be recorded via readout circuitry and permits the resetting of the pixel capacitors. Advantages of this invention over the prior art TFT technology results from our exploitation of the many benefits of CMOS technology. These benefits include much better circuit performance as well as design flexibility which enables us to fabricate a pixel array and readout circuitry together on a single wafer of silicon.